NORTH DAKOTA
DEPARTMENT *of* HEALTH

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March 29, 2016

Carl Daly, Director
Air Program (8P-AR)
U.S. EPA, Region 8
1595 Wynkoop Street
Denver, CO 80202-1129

Re: Data Requirements Rule SO_2 Designation Recommendation

Dear Mr. Daly:

In a letter dated September 16, 2015 to Gina McCarthy, Governor Dalrymple recommended that the area around the Leland Olds Station, Stanton Station and Coal Creek Station be designated attainment for the 1-hr SO_2 National Ambient Air Quality Standard. In a response to Governor Dalrymple from EPA dated February 16, 2016, it was indicated that the area around these electrical generating units would be classified as "unclassifiable". The reason for this designation was given that the modeling that was conducted used a 30-day rolling average emission rate for the Leland Olds Station instead of a 1-hr maximum emission rate.

Basin Electric Power Cooperative has prepared a revised modeling analysis for the Leland Olds Station which includes the Stanton Station and Coal Creek Station as nearby sources. The revised analysis indicates that a 1-hr emission rate of 1,430.3 lb/hr would be appropriate for a BART limit of 1,162.8 lb/hr on a 30-day rolling average basis. However, to be conservative, Basin Electric modeled an emission rate of 3,876 lb/hr which is more than three times the BART limit. The modeling analysis indicates that the area will still be in attainment with the 1-hr National Ambient Air Quality Standard for SO_2.

Attached is a copy of the revised modeling analysis report and a CD which contains the modeling files. The Department is submitting this updated information in support of Governor Dalrymple's recommendation that the area around these plants be designated as attainment.

If you have any questions, please feel free to contact us.

Sincerely,

Terry O'Clair

Terry L. O'Clair, P.E.
Director
Division of Air Quality

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xc: Cris Miller, Basin Electric

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AECOM Environment

Prepared for:
Basin Electric Power Cooperative
Bismarck, North Dakota

Prepared by:
AECOM
Chelmsford, MA
60427117.100
March 2016

Revised Characterization of 1-Hour SO_2 Concentrations in the Vicinity of the Coal Creek and Leland Olds Stations

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Revised Characterization of 1-Hour SO_2 Concentrations in the Vicinity of the Coal Creek and Leland Olds Stations

Prepared By: Mary Kaplan

Robert J. Paine
Reviewed By: Robert J. Paine

Melissa McLaughlin
PQR Review By: Melissa McLaughlin

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1.0 Introduction

The United States Environmental Protection Agency (EPA) is implementing the 2010 1-hour SO_2 National Ambient Air Quality Standard (NAAQS)[1] in an approach that involves either a dispersion modeling or monitoring approach to characterize local SO_2 concentrations near isolated emission sources. On March 20, 2015, EPA informed affected states that certain emission sources within their states will be addressed in an expedited[2] round of designations under the 1-hour SO_2 NAAQS due to terms of the SO_2 Consent Decree negotiated between the Sierra Club and EPA. The EPA intends to designate the affected areas as either unclassifiable/attainment, non-attainment or unclassifiable by July 2, 2016 after a review of available modeling or monitoring data to support the SO_2 concentration characterizations. Based upon a modeling demonstration submitted to the North Dakota Department of Health (NDDH) in the summer of 2015, NDDH recommended a finding of SO_2 NAAQS attainment in September 2015.

The affected sources evaluated in this analysis are the Leland Olds Station (LOS) and Coal Creek Station (CCS). The Stanton Station (STN) is not subject to the SO_2 Consent Decree; however, because of its proximity to LOS, it was included in this analysis per North Dakota Department of Health (NDDH) request. Figure 1-1 shows a map of the source locations and terrain in the vicinity.

EPA reviewed the modeling submitted by NDDH in 2015 and had a significant comment that one of the sources modeled, Leland Olds, used a 30-day average allowable SO_2 emission rate rather than a 1-hour emission rate. Therefore, EPA recommended an unclassifiable designation pending additional modeling results with a 1-hour emission rate tied to the 30-day allowable rate. As a result of this comment, we have determined an appropriately conservative 1-hour emission rate that has now been modeled along with the actual emissions from the other sources being included in the analysis. The results of this modeling continue to show attainment of the SO_2 NAAQS. As a result of this report and the accompanying submittal package, we expect that EPA will be able to update their recommended designation to attainment by the deadline of July 2, 2016.

1.1 Report Organization

Section 2 of this report describes the emission sources (LOS, CCS, and STN), and provides an updated discussion of the 1-hour SO_2 emission rate used for the LOS source. This section shows that there are no other nearby sources (i.e., within 10 km) that would interact with these three emission sources to cause a significant concentration gradient near any of the three sources. This section also describes the source of regional monitoring data that is used to represent distant source impacts. Section 3 describes the dispersion model approaches used in this study: the current default AERMOD modeling approach as well as the use of EPA-proposed low wind improvements to AERMOD. Justification for the use of the low wind improvements is provided in Appendices A, B, and C. Section 4 of the report describes the modeling results, and indicates that with modeling conducted

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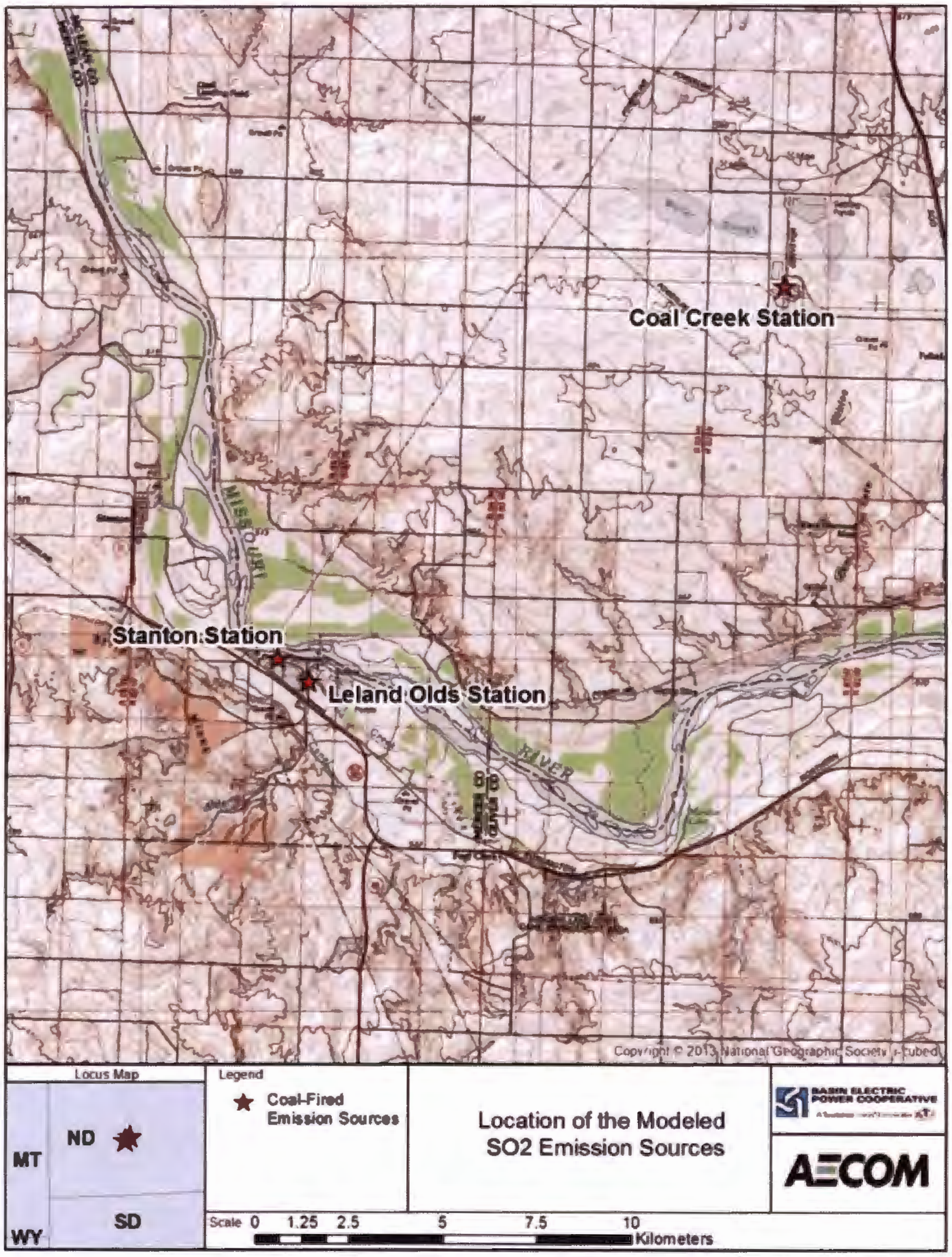
[1] 75 FR 35571 is the final rule for the 2010 SO_2 NAAQS.

[2] Information on the "SO_2 Consent Decree" is available at http://www.epa.gov/so2designations/data.html.

in accordance with the Modeling Technical Assistance Document[3], the characterization of SO_2 concentrations results in a finding of NAAQS attainment.

Figure 1-1: Topographical Map Showing Modeled SO_2 Emission Sources



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[3] http://www.epa.gov/airquality/sulfurdioxide/pdfs/SO2ModelingTAD.pdf.

2.0 Description of Modeled Emission Sources

2.1 Leland Olds Station

Leland Olds Station, owned by Basin Electric, consists of two coal-fired units. Unit 1 is a 220-megawatts unit (2,622 MMBtu/hr-nameplate); and Unit 2 is a 440-megawatt (5,130 MMBtu/hr nameplate) unit. The station is located four miles southeast of Stanton, North Dakota, along the Missouri River.

The two boilers' emissions are exhausted into a single 600-foot duel-flue stack, as shown in Figure 2-1 (the tallest of the three stacks shown). The area surrounding Leland Olds Station is considered rural with mostly flat terrain.

Figure 2-1: Leland Olds Station Photograph

Photograph source: Basin Electric https://www.basinelectric.com/Facilities/Leland-Olds/

For the 1-hour SO_2 NAAQS compliance modeling, EPA allows the use of actual emissions as long as they accurately represent actual conditions at the plant. In the middle of the 3-year modeling period (2012-2014), Basin Electric installed wet scrubbers to control SO_2 emissions on both units and redirected the exhausts from two separate stacks into a common 600-foot stack. Therefore, using a 3-year modeling period would not be representative of the current and future SO_2 emissions at Leland Olds. Since there is not yet a full three-year record of actual post-wet scrubber SO_2 emissions, the NDDH provided direction to use the Best Available Retrofit Technology (BART) Permit Allowable emission rate of 0.15 lb/MMBtu of SO_2 (equivalent to 1,162.8 lb/hr at full load conditions) for the prescrubbed time period. To be conservative, AECOM used in its 2015 modeling a constant maximum post-scrubber SO_2 emission rate of 1,162.8 lb/hr for the entire model simulation, which overstated the emissions after the scrubber installation, but which did not materially affect the modeling results. We also calculated an equivalent diameter for the two flues and used the 95th percentile flow rate and temperature to represent the post-scrubber conditions for each hour of the model simulation.

In its review of the 2015 modeling submitted by the NDDH and AECOM (available at http://www3.epa.gov/so2designations/round2/08_ND_tsd.pdf), EPA noted that:

"The emissions rate used for Leland Olds (1162.8 lb/hr) was based on continuous operation at the facility's SIP-approved maximum allowable 30-day rolling average rate of 0.15 lb/MMBtu. However, to properly account for short-term emissions spikes that can impact a one-hour rate but be smoothed out over a 30-day rate, the EPA recommends that an adjustment factor be applied to the modeled hourly emissions rate (See EPA's April 23, 2014 SO_2 Non-attainment Area Guidance at 25-37, and Appendices B, C and D). AECOM did not apply such a factor when modeling Leland Olds. Therefore, EPA finds that the AECOM modeling analysis cannot be relied upon for the purposes of designating the area of McLean County (full) and Mercer County (partial) as attainment, as the State recommended. Should the State submit an updated modeling analysis which meets EPA guidance and includes an appropriately adjusted emission rate for Leland Olds, EPA may base its final designation on that new information."

To address EPA's concerns, Basin Electric provided to AECOM updated hourly emissions information for the period when both units were scrubbed (from June 19, 2013 through December 31, 2015). Our findings from a review of this information are provided in Table 2-1.

Table 2-1: Review of 1-Hour to 30-day Leland Olds SO_2 Emissions (lb/hr)

lb/hr based on FGD Emissions	LOS 1&2
1-hour 99th Percentile	771.30
30-day rolling average 99th percentile	627.07
Ratio (1-hr/30-day)	1.23
30-day rolling average BART permit rate	1162.80
1-hour Rate Based on Ratio	1430.25

Based upon the information in Table 2-1, we considered the scaled 1-hour SO_2 emission rate for Leland Olds (1,430.25 lb/hr) as a starting point. To address potential peak 1-hour emissions, we increased that emission rate to a conservatively high value to be as high or higher than the likely peak emission rate: 0.5 lb/MMBtu times the full-load heat input rate of 7,752 MMBtu/hr (from the combined units), which is equal to 3,876 lb/hr for the combined units at Leland Olds.

Table 2-2 summarizes the emissions and stack parameters used in the revised AERMOD modeling.

Table 2-2: Revised Modeling Emissions and Exhaust Parameters

Parameter	**Leland Olds Station** (Unit 1 and 2 Modeled as a Combined Source)	**Stanton Station** (Unit 1 and 10 Modeled as a Combined Source)	**Coal Creek Station** (Unit 1 and 2 Modeled Separately)
SO_2 Emissions	3,876 lb/hr (0.5 lb/MMBtu times the full-load heat input rate)	2012-2014 actual hourly-variable	2012-2014 actual hourly-variable
Stack Height	182.88 m	77.724 m	205.74 m both units
Exit Temperature	335 K (95th percentile of the actual hourly velocity, post-scrubber period)	2012-2014 actual hourly-variable	2012-2014 actual hourly-variable
Exit Velocity	21.0 m/sec (95th percentile of the actual hourly velocity, post-scrubber period)	2012-2014 actual hourly-variable	2012-2014 actual hourly-variable
Diameter	9.97 m (equivalent diameter of two flues)	4.6 m	7.8 m each
Base Elevation	519 m	517 m	591 m

2.2 Stanton Station

Stanton Station is owned by Great River Energy and was named for its proximity to Stanton, North Dakota. It is located on a 250-acre site on the bank of the Missouri River. The plant has one turbine generator rated at 188 megawatts that is supplied by two boilers. Emissions from the two boilers are exhausted through a single 255-foot stack, as shown on Figure 2-2.

Although Stanton Station is not subject to the SO_2 Consent Decree, it was modeled because of its proximity to Leland Olds Station (less than a mile to the northwest). Similar to the Leland Olds Station, the area surrounding Stanton Station is rural with mostly flat terrain.

For the modeling analysis, we used 2012-2014 actual hourly SO_2 emissions, temperature and velocity data for the single stack at the facility.

Figure 2-2: Stanton Station Photograph

Photograph source: Great River Energy http://www.greatriverenergy.com/makingelectricity/coal/stantonstation.html

2.3 Coal Creek Station

Coal Creek Station features two units with a total generation capacity of more than 1,100 megawatts. The power plant is located about 50 miles north of Bismarck, North Dakota, near the city of Underwood. It is located about 10 miles (16.5 km) northeast of the LOS and STN stations.

Figure 2-3 shows the plant's two separate 675-foot stacks with the area surrounding the plant mostly rural with flat terrain.

For the modeling analysis, we used 2012-2014 actual hourly SO_2 emissions, temperature and velocity data. Each unit was modeled separately.

Figure 2-3: Coal Creek Station Photograph

Photograph source: Great River Energy http://www.greatriverenergy.com/makingelectricity/coal/coalcreekstation.html

2.4 Regional Background

According to the EPA March 1, 2011 Memorandum[4] and the analysis presented at the 2011 EPA modeling workshop[5], selection of regional background sources should be limited to 10 kilometers from the source location. Figure 2-4 shows the 10-km radius circle around LOS, CCS and regional SO_2 emission sources that we considered in this review. The nearest large SO_2 source is Stanton, which we modeled, and the next large source is more than 20 km away (Milton R. Young Station). At greater than 20 km, Milton R. Young would be expected to produce a uniform background influence. Therefore, this and any more distant sources would not be expected to interact with the modeled sources to cause a significant concentration gradient. For this 1-hour SO_2 NAAQS analysis, Stanton Station was the only background source considered in this modeling. The total concentration for 1-hour SO_2 NAAQS compliance was computed by adding the LOS, STN, and CCS predicted

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[4] http://www.epa.gov/scram001/guidance/clarification/Additional_Clarifications_AppendixW_Hourly-NO2-NAAQS_FINAL_03-01-2011.pdf

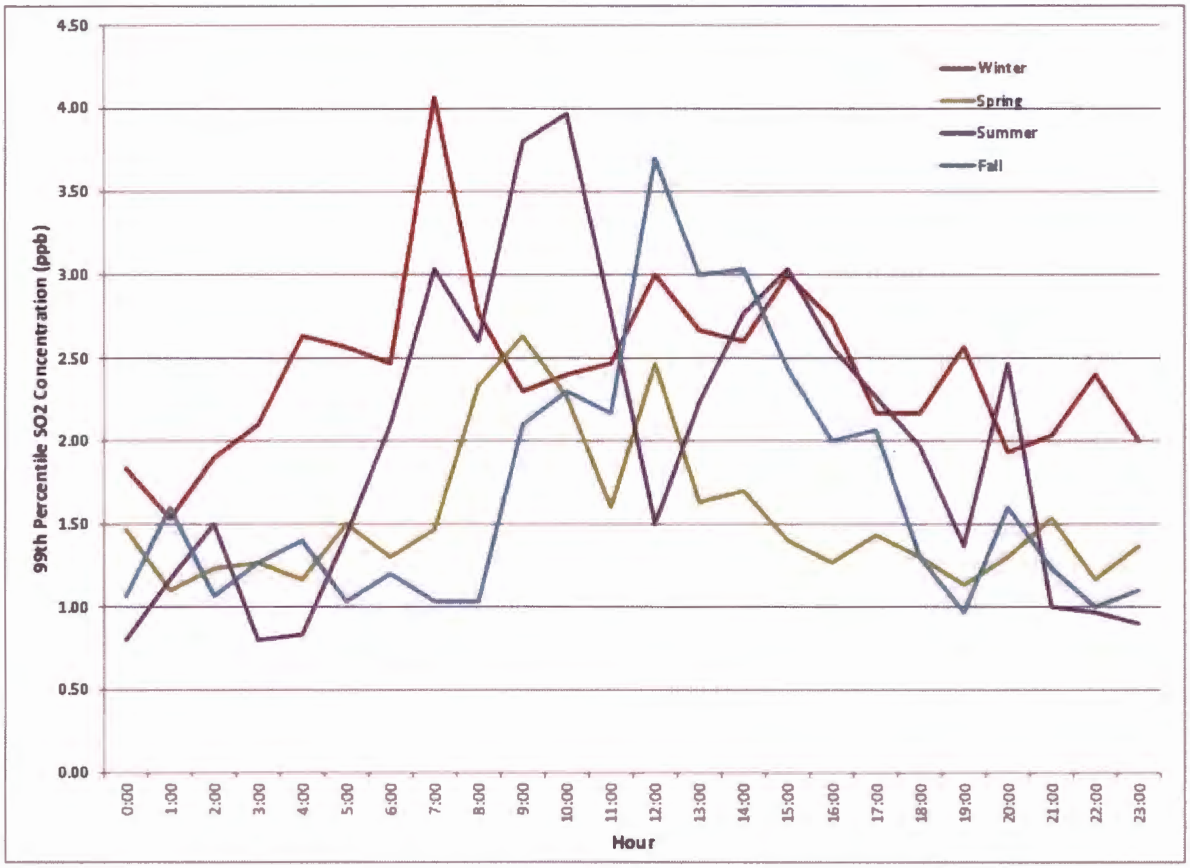
[5] Page 5 http://www.cleanairinfo.com/regionalstatelocalmodelingworkshop/archive/2011/Presentations/6-Thursday_AM/6-3_AB-3_Presentation_at_EPA_Modeling_Workshop.pdf

concentration to the regional background concentrations from the NDDH-approved Dunn Center monitor (location shown in Figure 3-5).

The background concentration was calculated as a 3-year (2012-2014) average of the 99th percentile by season and hour-of-day and added internally in AERMOD to the AERMOD-predicted concentration for comparison with the 1-hour SO_2 National Ambient Air Quality Standard (NAAQS) of 196.5 µg/m^3. The Dunn Center seasonal SO_2 concentrations are displayed in Figure 2-5.

Figure 2-4: SO_2 Regional Background Sources with Emissions Over 100 Tons

Figure 2-5: 2012-2014 Average 99th Percentile Concentration at Dunn Center SO_2 Monitor



3.0 Dispersion Modeling Approach

The suitability of an air quality dispersion model for a particular application is dependent upon several factors. The following selection criteria have been evaluated in selecting the model for this project:

- stack height relative to nearby structures;
- dispersion environment;
- local terrain; and
- Representative meteorological data.

The US EPA Guideline on Air Quality Models (Appendix W[6]) prescribes a set of approved models for regulatory applications for a wide range of source types and dispersion environments. Based on a review of the factors discussed below, the latest version of AERMOD (15181) was used to assess air quality impacts for the Coyote Station.

In a proposed rulemaking published in the July 29, 2015 Federal Register (80 FR 45340), the United States Environmental Protection Agency (EPA) released a revised version of AERMOD (15181), which replaces the previous version of AERMOD dated 14134. EPA proposed refinements to its preferred short-range model, AERMOD, involving low wind conditions. These refinements involve an adjustment to the computation of the friction velocity ("ADJ_U*") in the AERMET meteorological pre-processor and a higher minimum lateral wind speed standard deviation, sigma-v (σ_v), as incorporated into the "LOWWIND3" option. The proposal indicates that "the LOWWIND3 BETA option increases the minimum value of sigma-v from 0.2 to 0.3 m/s, uses the FASTALL approach to replicate the centerline concentration accounting for horizontal meander, but utilizes an effective sigma-y and eliminates upwind dispersion".[7] Additional technical support for the low wind speed options as an interim modeling approach is provided in Appendices A, B, and C.

As this report describes, the dispersion modeling analysis was conducted using both the current regulatory defaults and (for informational purposes) using proposed EPA changes to the preferred modeling approaches with beta ADJ_U* and LOWWIND3 option. Consistent with EPA's Appendix W review schedule, we anticipate that these proposed options could be promulgated as default options prior to the July 2, 2016 Consent Decree designation deadline, and therefore should be considered as more appropriate technical options to consider as supplemental information.

3.1 Good Engineering Practice Stack Height Analysis

Good engineering practice (GEP) stack height is defined as the stack height necessary to ensure that emissions from the stack do not result in excessive concentrations of any air pollutant as a result of atmospheric downwash, wakes, or eddy effects created by the source, nearby structures, or terrain features.

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[6] http://www.epa.gov/ttn/scram/guidance/guide/appw_05.pdf

[7] Addendum User's Guide for the AMS/EPA Regulatory Model – AERMOD
http://www.epa.gov/ttn/scram/models/aermod/aermod_userguide.zip

A GEP stack height analysis was performed for the boiler stacks at Leland Olds, Stanton, and Coal Creek Stations with the USEPA's Building Profile Input Program (BPIP). BPIP was used to develop the building/structural information required for input to AERMOD to simulate building downwash in the dispersion modeling.

The locations of the buildings/structures relative to the stack locations for Leland Olds, Stanton, and Coal Creek Stations are shown in Figures 3-1, 3-2, and 3-3, respectively. Since EPA's Technical Assistance Document for modeling[8] specifies that actual stack heights should be used in this modeling characterization of SO_2 concentrations, the GEP analysis was used to provide input of building dimensions to AERMOD, but not to change the stack height input from the actual value for input to the modeling.

3.2 Dispersion Environment

The application of AERMOD requires characterization of the local (within 3 kilometers) dispersion environment as either urban or rural, based on a US EPA-recommended procedure that characterizes an area by prevalent land use. This land use approach classifies an area according to 12 land use types. In this scheme, areas of industrial, commercial, and compact residential land use are designated urban. According to US EPA modeling guidelines, if more than 50% of an area within a 3-km radius of the facility is classified as rural, then rural dispersion coefficients are to be used in the dispersion modeling analysis. Conversely, if more than 50% of the area is urban, urban dispersion coefficients are used. As shown in Figure 1-1, the 3-km area surrounding each of the stations is rural. Therefore, rural dispersion was assumed for each of the plants being modeled.

3.3 Model Receptor Grid and Terrain

AERMAP (version 11103) was used to generate modeling receptors. Two identical Cartesian receptor grids were generated as an input to AERMOD with the following spacing.

- 0 km to 5 km with 100 meters spacing;
- 5 km to 10 km with 250 meters spacing.

The first grid was centered on the area between Leland Olds and Stanton Stations and the second grid was centered at the Coal Creek Station. For conservatism, no fence line receptors were excluded from the modeling.

Terrain elevations from 10-meter National Elevation Data (NED) from USGS were processed with AERMAP to develop the receptor terrain elevations required by AERMOD. Figure 3-4 shows the receptor network used in the modeling.

3.4 Meteorological Data Processing

AECOM held a conference call with NDDH on June 16, 2014 to discuss dispersion modeling assessments. NDDH advised to use NDDH-operated Beulah 10-meter tower data ("Beulah") and then provided AECOM with three years (2012-2014) of the Beulah meteorological surface data.

The meteorological data, listed below, was processed with the latest version of AERMET (15181) with both the EPA default and "ADJ_U*" options.

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[8] http://www.epa.gov/airquality/sulfurdioxide/pdfs/SO2ModelingTAD.pdf.

- The surface data consisted of 10-meter temperature, wind speed, wind direction, and 2-m temperature, and insolation. The quarterly data capture consistently exceeds 95%.
- Representative cloud cover data were automatically computed in AERMET Stage 3 from Hazen airport (15 km from Beulah).
- Beulah missing/calm winds were automatically substituted with Garrison airport (which has 1-minute data). Garrison airport data was introduced as 1-minute ASOS data in Stage 2 AERMET.
- Upper air soundings were from Bismarck, ND and missing soundings were substituted with Glasgow, MT station.

Figure 3-5 shows the locations of the meteorological stations mentioned above in relation to the modeled stations, as well as the SO_2 background station discussed below. Figure 3-6 shows the Beulah 3-year wind rose.

AERMET requires specification of site characteristics including surface roughness, Bowen ratio, and albedo. These parameters were developed according to the guidance provided by EPA in the most recent revision of the AERMOD Implementation Guide (AIG)[9].

The AIG provides the following recommendations for determining the site characteristics:

1. The determination of the surface roughness length should be based on an inverse distance weighted geometric mean for a default upwind distance of 1 kilometer relative to the measurement site. Surface roughness length may be varied by sector to account for variations in land cover near the measurement site; however, the sector widths should be no smaller than 30 degrees.
2. The determination of the Bowen ratio should be based on a simple un-weighted geometric mean (i.e., no direction or distance dependency) for a representative domain, with a default domain defined by a 10-km by 10-km region centered on the measurement site.
3. The determination of the albedo should be based on a simple un-weighted arithmetic mean (i.e., no direction or distance dependency) for the same representative domain as defined for Bowen ratio, with a default domain defined by a 10-km by 10-km region centered on the measurement site.

For this application, twelve wind direction sectors were selected around the primary site of the Beulah tower, as shown in Figure 3-7. A secondary set of surface characteristics for the twelve sectors was developed around the NWS Hazen airport. In AERMET Stage 3, the primary set of characteristics was applied for those hours in which the onsite data are used and the secondary set was applied for those hours in which the NWS surface file or 1-minute ASOS wind data are substituted for missing or calm onsite data.

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[9] US EPA 2015. AERMOD Implementation Guide (AIG). Office of Air Quality Planning and Standards, Research Triangle Park, NC. August.
http://www.epa.gov/ttn/scram/7thconf/aermod/aermod_implmtn_guide_3August2015.pdf

Table 3-1: AERSURFACE Bowen Ratio Condition Designations for Beulah Site

Month	Bowen Ratio Category		
	2012	2013	2014
January	Dry	Dry	Average
February	Wet	Average	Average
March	Average	Average	Average
April	Wet	Wet	Wet
May	Average	Wet	Wet
June	Average	Wet	Average
July	Average	Average	Dry
August	Dry	Wet	Wet
September	Dry	Wet	Average
October	Wet	Wet	Average
November	Wet	Average	Wet
December	Wet	Wet	Dry

The AERSURFACE seasonal categories by month were developed for each modeled year and they were applied for the primary (Beulah site) and secondary (Hazen airport) site, as shown in Table 3-2. A month was selected as a "winter with continuous snow on the ground" if a month had at least half of the days with recorded snow on the ground. Daily snow cover records were obtained for the Garrison and Bismarck airports from the National Climatic Data Center (NCDC)[11].

Table 3-2: Selected Seasonal Categories for AERSURFACE

Season Description	2012	2013	2014
Late autumn after frost and harvest, or winter with no snow	1,2,3	3,4	3
Winter with continuous snow on the ground	11, 12	12,1,2	11, 12, 1, 2
Transitional spring	4, 5	5	4, 5
Midsummer with lush vegetation	6,7,8	6,7,8	6,7,8
Autumn with unharvested cropland	9,10	9,10,11	9,10

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[11] http://www.ncdc.noaa.gov/cdo-web/search

Figure 3-1: Stacks and Buildings in the GEP Analysis for Leland Olds Station

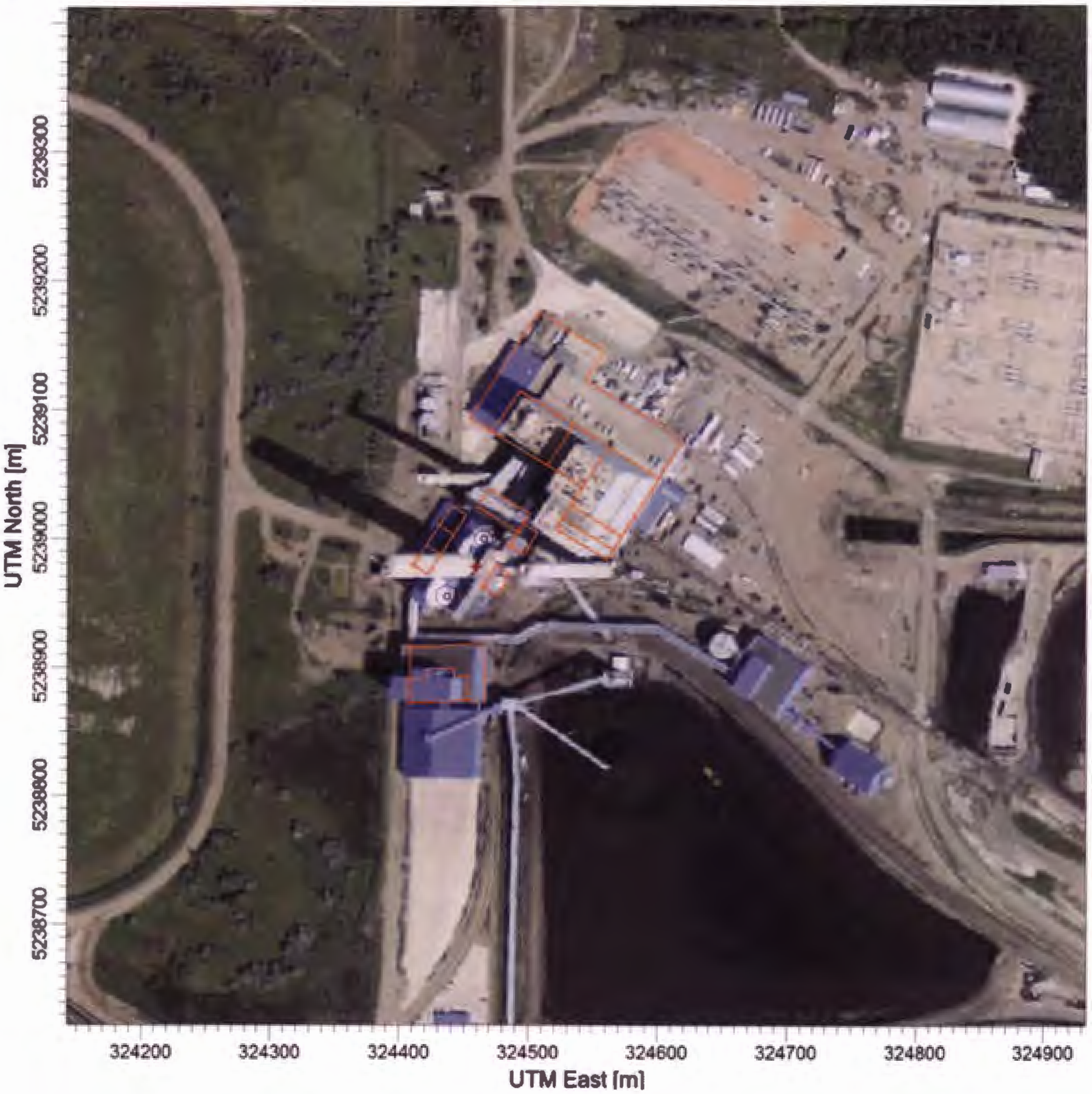


Figure 3-2: Stacks and Buildings Used in the GEP Analysis for Stanton Station

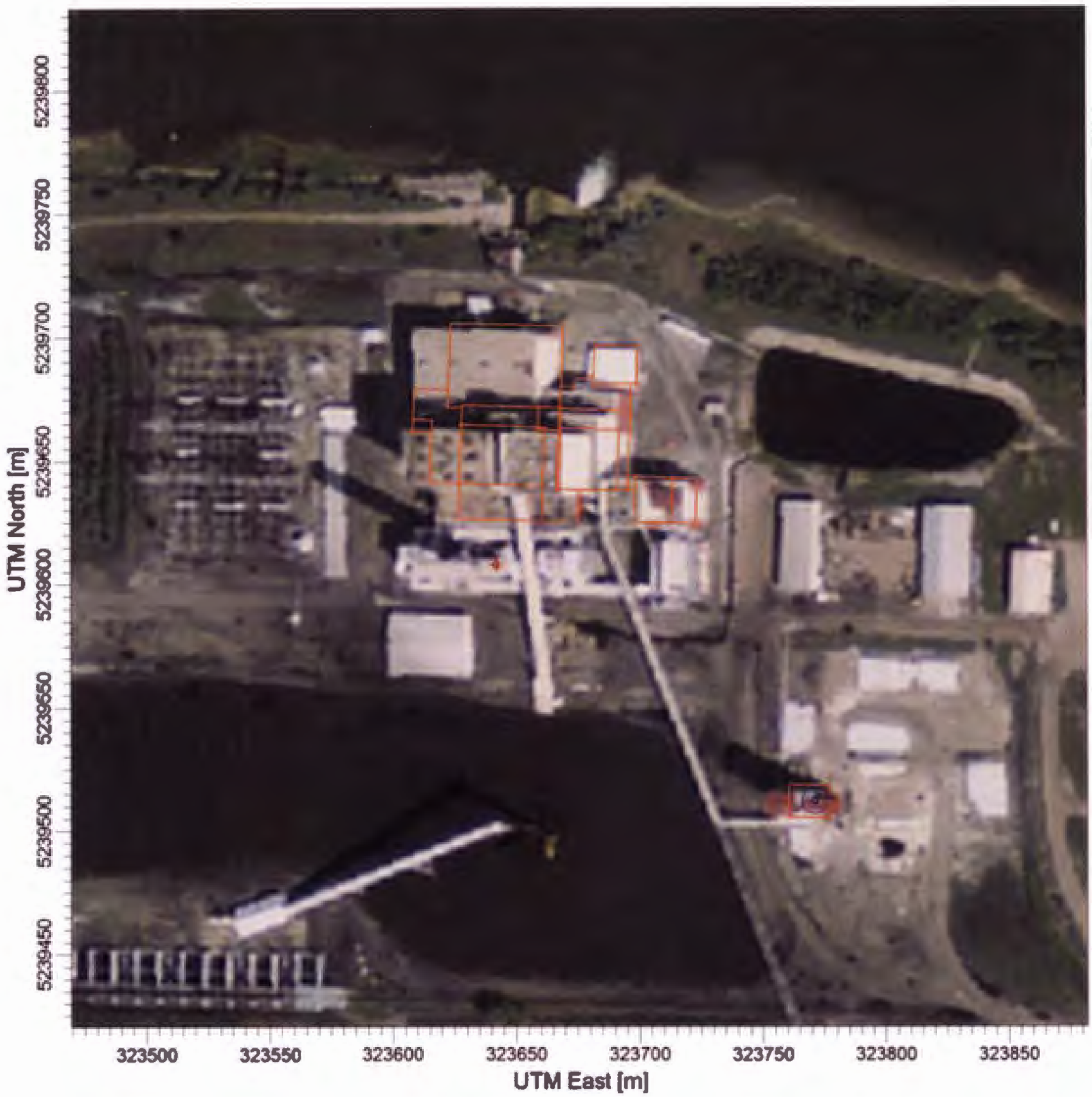


Figure 3-3: Stacks and Buildings Used in the GEP Analysis for Coal Creek Station

Figure 3-4: Modeling Receptor Grid

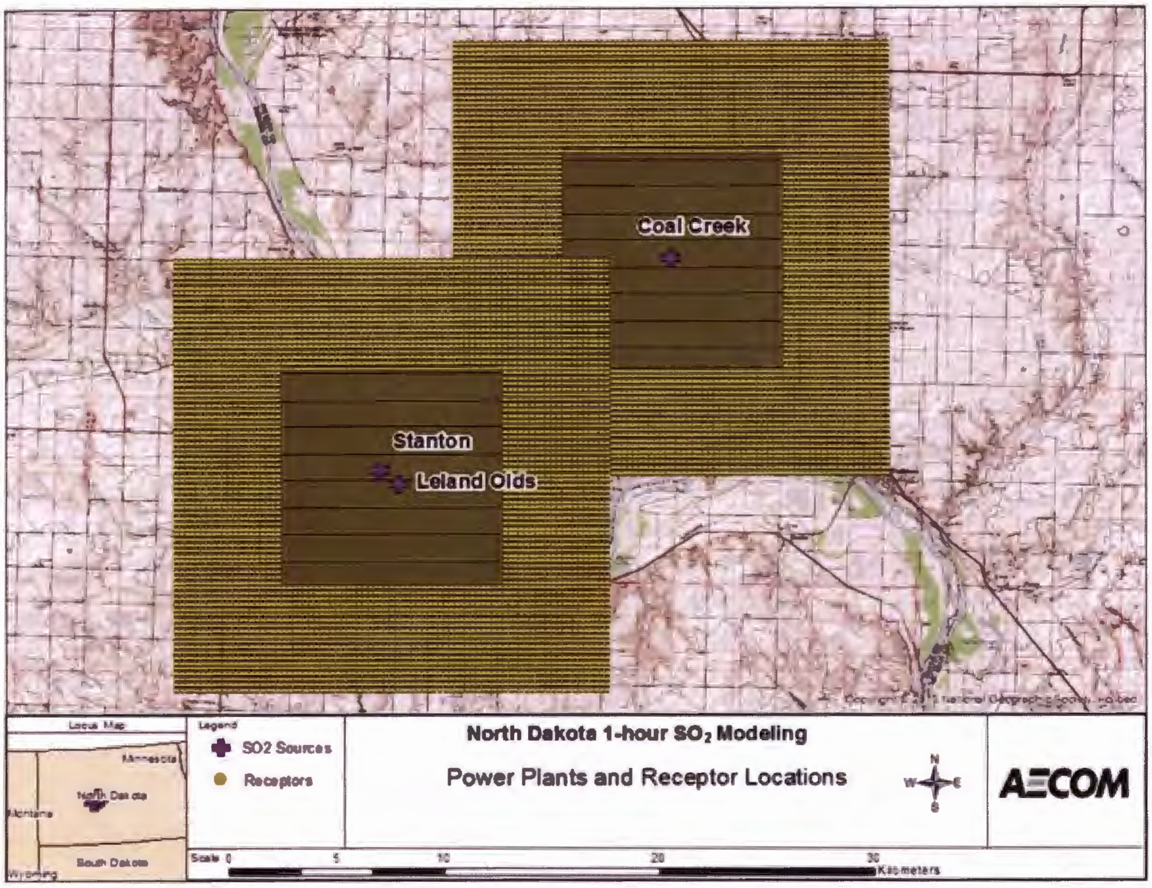


Figure 3-5: Location of Meteorological Stations and SO_2 Monitor Relative to the Modeled Sources

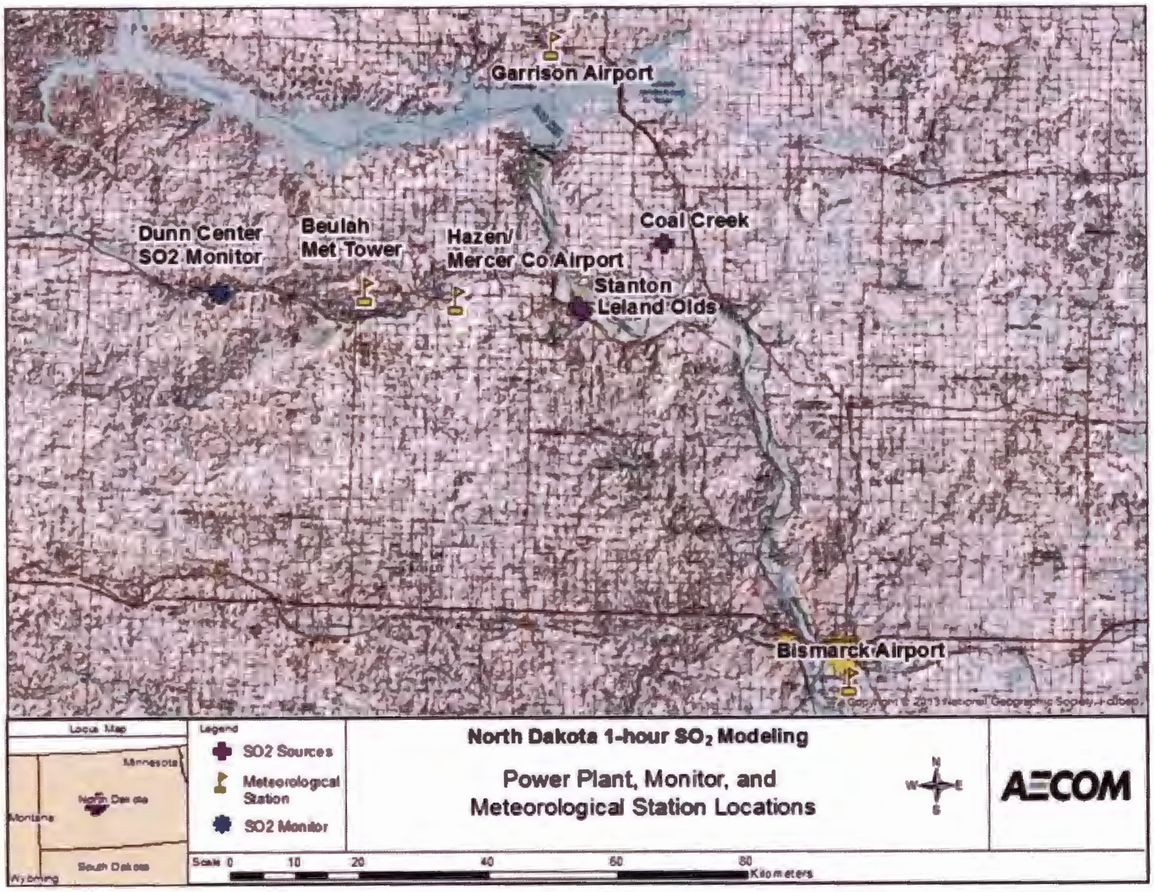
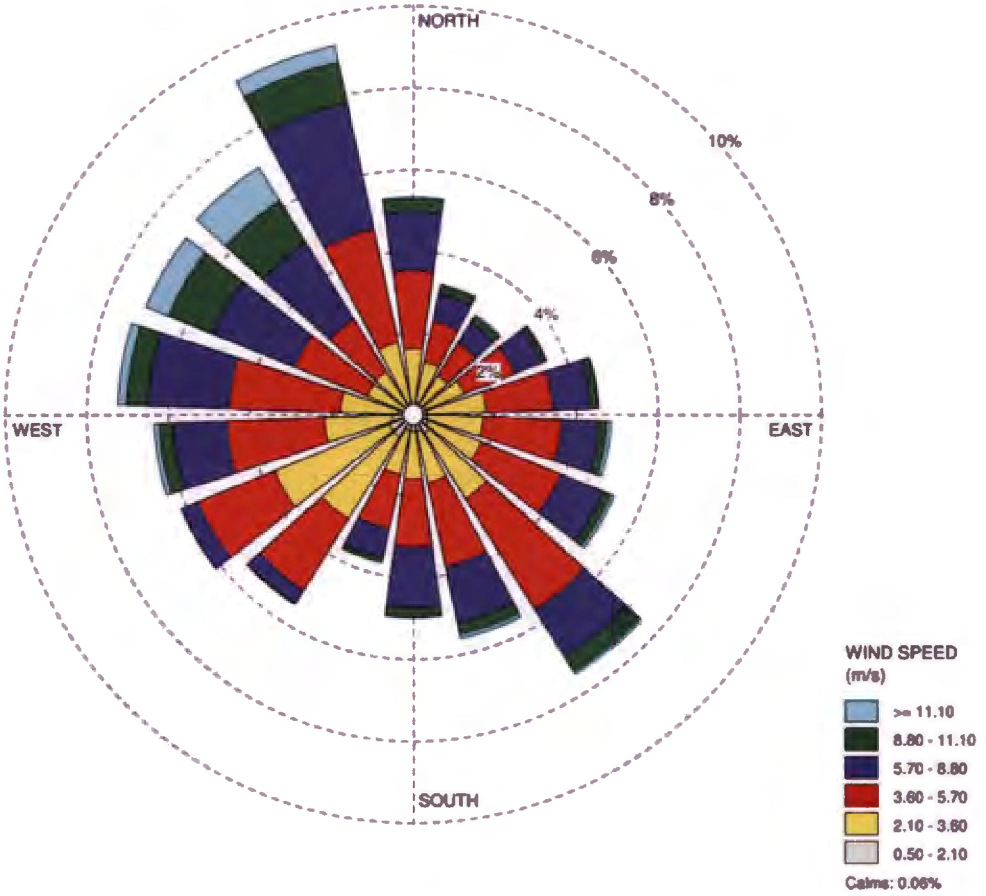


Figure 3-6: Beulah Wind Rose (2012-2014)

WIND ROSE PLOT: **Beulah 10-meter Tower Wind Rose** **2012-2014**	DISPLAY: **Wind Speed** **Direction (blowing from)**



COMMENTS:	DATA PERIOD: **Start Date: 1/1/2012 - 00:00** **End Date: 12/31/2014 - 23:00**	COMPANY NAME:	
		MODELER:	
	CALM WINDS: **0.06%**	TOTAL COUNT: **26304 hrs.**	
	AVG. WIND SPEED: **5.04 m/s**	DATE: **8/26/2015**	PROJECT NO.:

Figure 3-7: Land Use Sectors Around Beulah Tower for AERSURFACE

4.0 AERMOD Modeling Results

The modeling was conducted with the EPA default option and beta ADJ_U* with LOWWIND3 options. The concentration isopleths for the default option and ADJ_U* with LOWWIND3 are plotted in Figures 4-1 and 4-2, respectively. The figures indicate that there is a peak area east of Leland Olds and Stanton Stations and another area is northeast of Coal Creek Station.

Table 4-1 shows the design concentration from each source, without background concentration added. Stanton and Coal Creek Stations have the highest impacts and Leland Olds Station is predicted to have minimal impact (as expected after wet SO_2 scrubbers installation).

Table 4-2 shows the NAAQS compliance modeling results of the three stations and monitoring background combined. The peak design concentration occurs in flat terrain about 2 kilometers to the west of Leland Olds and Stanton Stations. The results with both options tested show compliance with the 1-hour SO_2 NAAQS by a comfortable margin, especially with the EPA-proposed low wind options employed using AERMOD version 15181.

This modeling analysis supports the designation of the area in the vicinity of the Leland Olds and Coal Creek Stations as being in attainment of the 1-hour SO_2 NAAQS.

For informational purposes, Tables 4-3 and 4-4 summarize source culpability at the two peak impact locations. They show that in the Leland Olds and Stanton Station area, Stanton Station generally dominates the impact. At the Coal Creek Station area of the peak impact, Coal Creek Station has the highest contribution with Stanton and Leland Olds Stations having lesser contribution to the total impact.

Table 4-1: AERMOD Modeled Peak Design SO_2 Concentrations(1) from Each Modeled Facility

Modeling Option	Leland Olds Station Modeled Design Concentration ($\mu g/m^3$)	Stanton Station Modeled Design Concentration ($\mu g/m^3$)	Coal Creek Station Modeled Design Concentration ($\mu g/m^3$)	NAAQS ($\mu g/m^3$)
Default	97.4	160.8	102.7	196.5
Beta u* and LOWWIND3	87.4	114.0	92.9	196.5

(1) The "design concentration" is the 99th percentile peak daily 1-hour maximum concentration, averaged over the 3 years

Table 4-2: AERMOD Modeled Design SO_2 Concentrations from All Facilities Combined (including Background Concentrations)

Modeling Option	Leland Olds, Stanton, Coal Creek Stations Modeled Design Concentration (μg/m^3)	Background Design Concentration from Dunn Center (μg/m^3) (1)	Total Design Concentration (μg/m^3)	NAAQS (μg/m^3)
Default	163.8	3.4	167.3	196.5
Beta u* and LOWWIND3	120.4	8.0	128.4	196.5

(1) The background concentrations are different for the two options because the total design concentration computed internally by AERMOD occurs on a different hour of the modeled period.

Table 4-3: Source Culpability for Two Peak Impact Receptors with Default Option

Peak Location	Coal Creek Station Modeled Peak Concentration (μg/m^3)	Stanton Station Modeled Peak Concentration (μg/m^3)	Leland Olds Station Modeled Peak Concentration (μg/m^3)	Background Design Concentration from Dunn Center (μg/m^3) (1)	Total Design Concentration (μg/m^3)	NAAQS (μg/m^3)
Leland Olds & Stanton Area (1)	3.2	160.6	0.0	3.5	167.3	196.5
Coal Creek Area (2)	109.4	4.4	16.0	8.1	138.9	196.5

(1) Peak location near Leland Olds and Stanton is at x=320045.00, y=5238393.00
(2) Peak location near Coal Creek is at x=339485.00, y=5251390.00

Table 4-4: Source Culpability for Two Peak Impact Receptors with ADJ_U* and LOWWIND Options

Peak Location	Coal Creek Station Modeled Peak Concentration (μg/m^3)	Stanton Station Modeled Peak Concentration (μg/m^3)	Leland Olds Station Modeled Peak Concentration (μg/m^3)	Background Design Concentration from Dunn Center (μg/m^3) (1)	Total Design Concentration (μg/m^3)	NAAQS (μg/m^3)
Leland Olds & Stanton Area (1)	0.0	117.2	0.0	3.4	120.6	196.5
Coal Creek Area (2)	92.9	4.7	23.5	7.1	128.4	196.5

(1) Peak location near Leland Olds and Stanton is at x=320045.00, y=5238393.00
(2) Peak location near Coal Creek is at x=340285.00, y=5251990.00

Figure 4-1: 99th Percentile 3-Year Average 1-Hour SO_2 Concentration Isopleths with Default Option

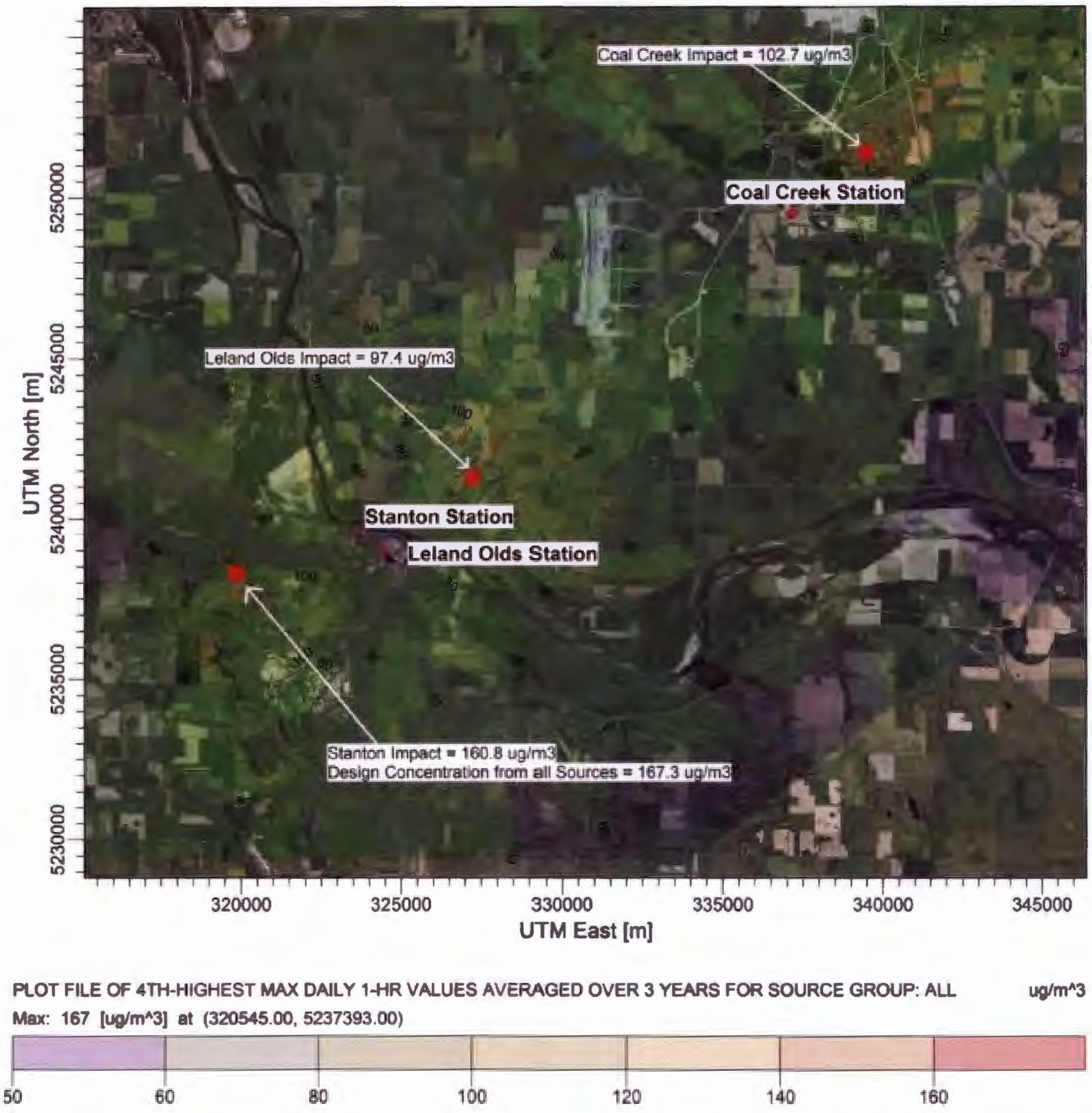
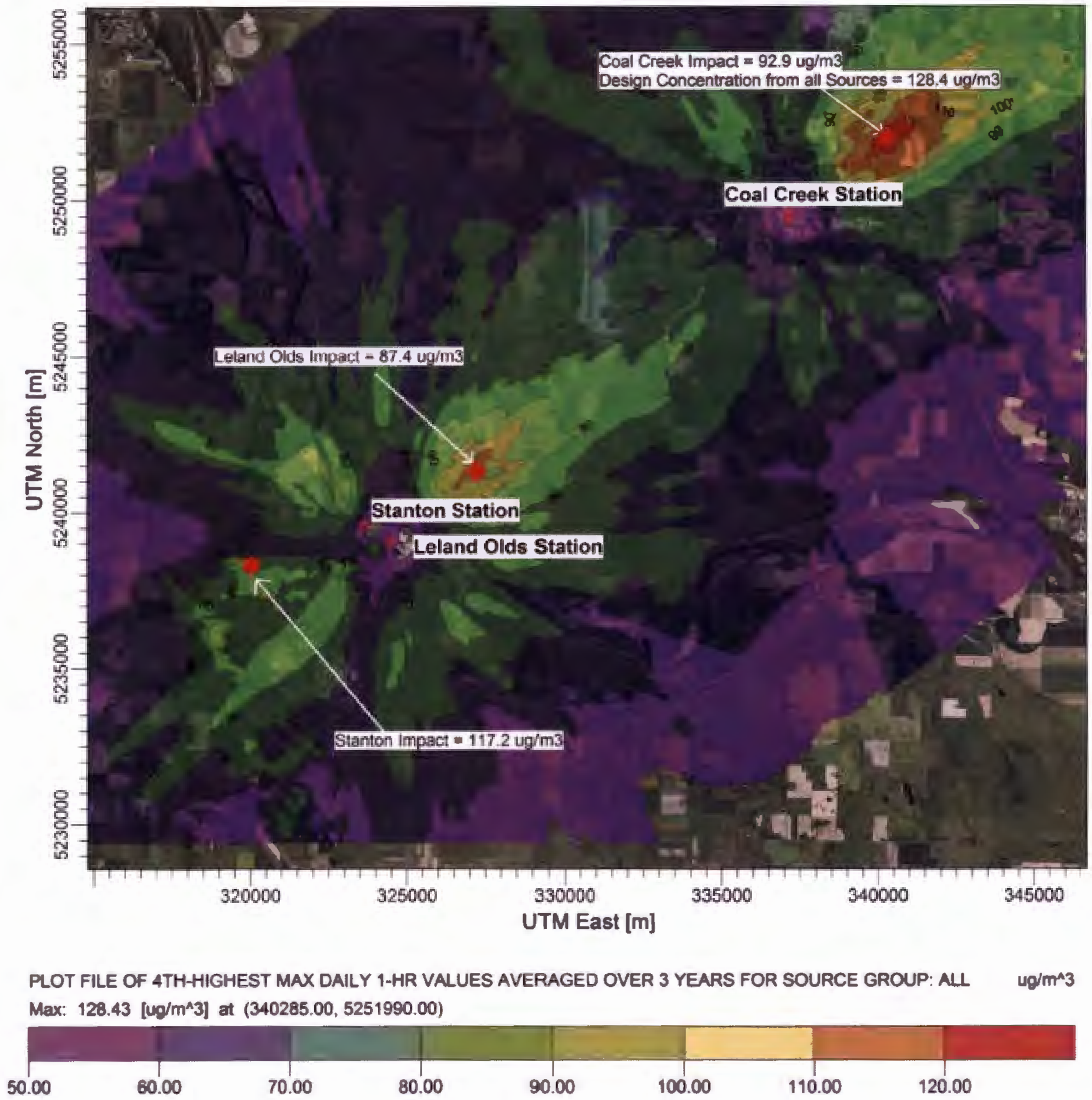


Figure 4-2: 99^{th} Percentile 3-Year 1-Hour SO_2 Concentration Isopleths with ADJ_U* and LOWWIND Options



faulty and needs to be replaced by the ADJ_U* approach. The improvements due to the LOWWIND3 algorithm are demonstrated with the low wind model evaluations reported by the presentations[3] at the 11th EPA modeling conference

3. **The data bases which are necessary to perform the analysis are available and adequate.**

   Routine meteorological databases that are already available are sufficient for exercising this low wind options. There are no special database requirements for the use of these options.

4. **Appropriate performance evaluations of the model have shown that the model is not biased toward underestimates.**

   The studies cited above by EPA and AECOM provide this demonstration.

5. **A protocol on methods and procedures to be followed has been established.**

   This report documents the methods and procedures to be followed.

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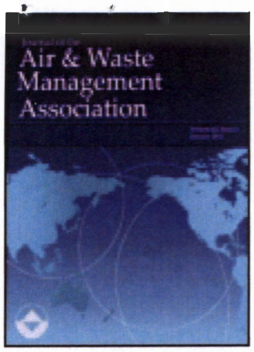
[3] http://www.epa.gov/ttn/scram/11thmodconf/presentations/1-5_Proposed_Updates_AERMOD_System.pdf and http://www.epa.gov/ttn/scram/11thmodconf/presentations/2-3_Low_Wind_Speed_Evaluation_Study.pdf.

Appendix B

Evaluation of Low Wind Modeling Approaches for Two Tall-Stack Databases Technical Paper



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Evaluation of low wind modeling approaches for two tall-stack databases

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TECHNICAL PAPER

Evaluation of low wind modeling approaches for two tall-stack databases

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The performance of the AERMOD air dispersion model under low wind speed conditions, especially for applications with only one level of meteorological data and no direct turbulence measurements or vertical temperature gradient observations, is the focus of this study. The analysis documented in this paper addresses evaluations for low wind conditions involving tall stack releases for which multiple years of concurrent emissions, meteorological data, and monitoring data are available. AERMOD was tested on two field-study databases involving several SO_2 *monitors and hourly emissions data that had sub-hourly meteorological data (e.g., 10-min averages) available using several technical options: default mode, with various low wind speed beta options, and using the available sub-hourly meteorological data. These field study databases included (1) Mercer County, a North Dakota database featuring five* SO_2 *monitors within 10 km of the Dakota Gasification Company's plant and the Antelope Valley Station power plant in an area of both flat and elevated terrain, and (2) a flat-terrain setting database with four* SO_2 *monitors within 6 km of the Gibson Generating Station in southwest Indiana. Both sites featured regionally representative 10-m meteorological databases, with no significant terrain obstacles between the meteorological site and the emission sources. The low wind beta options show improvement in model performance helping to reduce some of the overprediction biases currently present in AERMOD when run with regulatory default options. The overall findings with the low wind speed testing on these tall stack field-study databases indicate that AERMOD low wind speed options have a minor effect for flat terrain locations, but can have a significant effect for elevated terrain locations. The performance of AERMOD using low wind speed options leads to improved consistency of meteorological conditions associated with the highest observed and predicted concentration events. The available sub-hourly modeling results using the Sub-Hourly AERMOD Run Procedure (SHARP) are relatively unbiased and show that this alternative approach should be seriously considered to address situations dominated by low-wind meander conditions.*

Implications: AERMOD was evaluated with two tall stack databases (in North Dakota and Indiana) in areas of both flat and elevated terrain. AERMOD cases included the regulatory default mode, low wind speed beta options, and use of the Sub-Hourly AERMOD Run Procedure (SHARP). The low wind beta options show improvement in model performance (especially in higher terrain areas), helping to reduce some of the overprediction biases currently present in regulatory default AERMOD. The SHARP results are relatively unbiased and show that this approach should be seriously considered to address situations dominated by low-wind meander conditions.

Introduction

During low wind speed (LWS) conditions, the dispersion of pollutants is limited by diminished fresh air dilution. Both monitoring observations and dispersion modeling results of this study indicate that high ground-level concentrations can occur in these conditions. Wind speeds less than 2 m/sec are generally considered to be "low," with steady-state modeling assumptions compromised at these low speeds (Pasquill et al., 1983). Pasquill and Van der Hoven (1976) recognized that for such low wind speeds, a plume is unlikely to have any definable travel. Wilson et al. (1976) considered this wind speed (2 m/sec) as the upper limit for conducting tracer experiments in low wind speed conditions.

Anfossi et al. (2005) noted that in LWS conditions, dispersion is characterized by meandering horizontal wind oscillations. They reported that as the wind speed decreases, the standard deviation of the wind direction increases, making it more difficult to define a mean plume direction. Sagendorf and Dickson (1974) and Wilson et al. (1976) found that under LWS conditions, horizontal diffusion was enhanced because of this meander and the resulting ground-level concentrations could be much lower than that predicted by steady-state Gaussian plume models that did not account for the meander effect.

A parameter that is used as part of the computation of the horizontal plume spreading in the U.S. Environmental Protection Agency (EPA) preferred model, AERMOD (Cimorelli et al., 2005), is the standard deviation of the crosswind component, σ_v, which can be parameterized as being proportional to the friction velocity, u_* (Smedman, 1988; Mahrt, 1998). These investigators

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found that there was an elevated minimum value of σ_v that was attributed to meandering. While at higher wind speeds small-scale turbulence is the main source of variance, lateral meandering motions appear to exist in all conditions. Hanna (1990) found that σ_v maintains a minimum value of about 0.5 m/sec even as the wind speed approaches zero. Chowdhury et al. (2014) noted that a minimum σ_v of 0.5 m/s is a part of the formulation for the SCICHEM model. Anfossi (2005) noted that meandering exists under all meteorological conditions regardless of the stability or wind speed, and this phenomenon sets a lower limit for the horizontal wind component variances as noted by Hanna (1990) over all types of terrain.

An alternative method to address wind meander was attempted by Sagendorf and Dickson (1974), who used a Gaussian model, but divided each computation period into sub-hourly (2-min) time intervals and then combined the results to determine the total hourly concentration. This approach directly addresses the wind meander during the course of an hour by using the sub-hourly wind direction for each period modeled. As we discuss later, this approach has some appeal because it attempts to use direct wind measurements to account for sub-hourly wind meander. However, the sub-hourly time interval must not be so small as to distort the basis of the horizontal plume dispersion formulation in the dispersion model (e.g., AERMOD). Since the horizontal dispersion shape function for stable conditions in AERMOD is formulated with parameterizations derived from the 10-min release and sampling times of the Prairie Grass experiment (Barad, 1958), it is appropriate to consider a minimum sub-hourly duration of 10 minutes for such modeling using AERMOD. The Prairie Grass formulation that is part of AERMOD may also result in an underestimate of the lateral plume spread shape function in some cases, as reported by Irwin (2014) for Kincaid SF_6 releases. From analyses of hourly samples of SF_6 taken at Kincaid (a tall stack source), Irwin determined that the lateral dispersion simulated by AERMOD could underestimate the lateral dispersion (by 60%) for near-stable conditions (conditions for which the lateral dispersion formulation that was fitted to the Project Prairie Grass data could affect results).

It is clear from the preceding discussion that the simulation of pollutant dispersion in LWS conditions is challenging. In the United States, the use of steady-state plume models before the introduction of AERMOD in 2005 was done with the following rule implemented by EPA: "When used in steady-state Gaussian plume models, measured site-specific wind speeds of less than 1 m/sec but higher than the response threshold of the instrument should be input as 1 m/sec" (EPA, 2004).

With EPA's implementation of a new model, AERMOD, in 2005 (EPA, 2005), input wind speeds lower than 1 m/sec were allowed due to the use of a meander algorithm that was designed to account for the LWS effects. As noted in the AERMOD formulation document (EPA, 2004), "AERMOD accounts for meander by interpolating between two concentration limits: the coherent plume limit (which assumes that the wind direction is distributed about a well-defined mean direction with variations due solely to lateral turbulence) and the random plume limit (which assumes an equal probability of any wind direction)."

A key aspect of this interpolation is the assignment of a time scale (= 24 hr) at which mean wind information at the source is no longer correlated with the location of plume material at a downwind receptor (EPA, 2004). The assumption of a full diurnal cycle relating to this time scale tends to minimize the weighting of the random plume component relative to the coherent plume component for 1-hr time travel. The resulting weighting preference for the coherent plume can lead to a heavy reliance on the coherent plume, ineffective consideration of plume meander, and a total concentration overprediction.

For conditions in which the plume is emitted aloft into a stable layer or in areas of inhomogeneous terrain, it would be expected that the decoupling of the stable boundary layer relative to the surface layer could significantly shorten this time scale. These effects are discussed by Brett and Tuller (1991), where they note that lower wind autocorrelations occur in areas with a variety of roughness and terrain effects. Perez et al. (2004) noted that the autocorrelation is reduced in areas with terrain and in any terrain setting with increasing height in stable conditions when decoupling of vertical motions would result in a "loss of memory" of surface conditions. Therefore, the study reported in this paper has reviewed the treatment of AERMOD in low wind conditions for field data involving terrain effects in stable conditions, as well as for flat terrain conditions, for which convective (daytime) conditions are typically associated with peak modeled predictions.

The computation of the AERMOD coherent plume dispersion and the relative weighting of the coherent and random plumes in stable conditions are strongly related to the magnitude of σ_v, which is directly proportional to the magnitude of the friction velocity. Therefore, the formulation of the friction velocity calculation and the specification of a minimum σ_v value are also considered in this paper. The friction velocity also affects the internally calculated vertical temperature gradient, which affects plume rise and plume–terrain interactions, which are especially important in elevated terrain situations.

Qian and Venkatram (2011) discuss the challenges of LWS conditions in which the time scale of wind meandering is large and the horizontal concentration distribution can be non-Gaussian. It is also quite possible that wind instrumentation cannot adequately detect the turbulence levels that would be useful for modeling dispersion. They also noted that an analysis of data from the Cardington tower indicates that Monin–Obukhov similarity theory underestimates the surface friction velocity at low wind speeds. This finding was also noted by Paine et al. (2010) in an independent investigation of Cardington data as well as data from two other research-grade databases. Both Qian and Venkatram and Paine et al. proposed similar adjustments to the calculation of the surface friction velocity by AERMET, the meteorological processor for AERMOD. EPA incorporated the Qian and Venkatram suggested approach as a "beta option" in AERMOD in late 2012 (EPA, 2012). The same version of AERMOD also introduced low wind modeling options affecting the minimum value of σ_v and the weighting of the meander component that were used in the Test Cases 2–4 described in the following.

AERMOD's handling of low wind speed conditions, especially for applications with only one level of meteorological data and no direct turbulence measurements or vertical temperature gradient observations, is the focus of this study. Previous evaluations of AERMOD for low wind speed conditions (e.g., Paine et al., 2010) have emphasized low-level tracer release studies conducted in the 1970s and have utilized results of researchers such as Luhar and Rayner (2009). The focus of the study reported here is a further evaluation of AERMOD, but focusing upon tall-stack field databases. One of these databases was previously evaluated (Kaplan et al., 2012) with AERMOD Version 12345, featuring a database in Mercer County, North Dakota. This database features five SO_2 monitors in the vicinity of the Dakota Gasification Company plant and the Antelope Valley Station power plant in an area of both flat and elevated terrain. In addition to the Mercer County, ND, database, this study considers an additional field database for the Gibson Generating Station tall stack in flat terrain in southwest Indiana.

EPA released AERMOD version 14134 with enhanced low wind model features that can be applied in more than one combination. There is one low wind option (beta u_*) applicable to the meteorological preprocessor, AERMET, affecting the friction velocity calculation, and a variety of options available for the dispersion model, AERMOD, that focus upon the minimum σ_v specification. These beta options have the potential to reduce the overprediction biases currently present in AERMOD when run for neutral to stable conditions with regulatory default options (EPA, 2014a, 2014b). These new low wind options in AERMET and AERMOD currently require additional justification for each application in order to be considered for use in the United States. While EPA has conducted evaluations on low-level, nonbuoyant studies with the AERMET and AERMOD low wind speed beta options, it has not conducted any new evaluations on tall stack releases (U.S. EPA, 2014a, 2014b). One of the purposes of this study was to augment the evaluation experiences for the low wind model approaches for a variety of settings for tall stack releases.

This study also made use of the availability of sub-hourly meteorological observations to evaluate another modeling approach. This approach employs AERMOD with sub-hourly meteorological data and is known as the Sub-Hourly AERMOD Run Procedure or SHARP (Electric Power Research Institute [EPRI], 2013). Like the procedure developed by Sagendorf and Dickson as described earlier, SHARP merely subdivides each hour's meteorology (e.g., into six 10-min periods) and AERMOD is run multiple times with the meteorological input data (e.g., minutes 1–10, 11–20, etc.) treated as "hourly" averages for each run. Then the results of these runs are combined (averaged). In our SHARP runs, we did not employ any observed turbulence data as input. This alternative modeling approach (our Test Case 5 as discussed later) has been compared to the standard hourly AERMOD modeling approach for default and low wind modeling options (Test Cases 1–4 described later, using hourly averaged meteorological data) to determine whether it should be further considered as a viable technique. This study provides a discussion of the various low wind speed modeling options and the field study databases that were tested, as well as the modeling results.

Modeling Options and Databases for Testing

Five AERMET/AERMOD model configurations were tested for the two field study databases, as listed in the following. All model applications used one wind level, a minimum wind speed of 0.5 m/sec, and also used hourly average meteorological data with the exception of SHARP applications. As already noted, Test Cases 1–4 used options available in the current AERMOD code. The selections for Test Cases 1–4 exercised these low wind speed options over a range of reasonable choices that extended from no low wind enhancements to a full treatment that incorporates the Qian and Venkatram (2011) u_* recommendations as well as the Hanna (1990) and Chowdhury (2014) minimum σ_v recommendations (0.5 m/sec). Test Case 5 used sub-hourly meteorological data processed with AERMET using the beta u_* option for SHARP applications. We discuss later in this document our recommendations for SHARP modeling without the AERMOD meander component included.

Test Case 1: AERMET and AERMOD in default mode.

Test Case 2: Low wind beta option for AERMET and default options for AERMOD (minimum σ_v value of 0.2 m/sec).

Test Case 3: Low wind beta option for AERMET and the LOWWIND2 option for AERMOD (minimum σ_v value of 0.3 m/sec).

Test Case 4: Low wind beta option for AERMET and the LOWWIND2 option for AERMOD (minimum σ_v value of 0.5 m/sec).

Test Case 5: Low wind beta option for AERMET and AERMOD run in sub-hourly mode (SHARP) with beta u*option.

The databases that were selected for the low wind model evaluation are listed in Table 1 and described next. They were selected due to the following attributes:

- They feature multiple years of hourly SO_2 monitoring at several sites.
- Emissions are dominated by tall stack sources that are available from continuous emission monitors.
- They include sub-hourly meteorological data so that the SHARP modeling approach could be tested as well.
- There are representative meteorological data from a single-level station typical of (or obtained from) airport-type data.

Mercer County, North Dakota. An available 4-year period of 2007–2010 was used for the Mercer County, ND, database with five SO_2 monitors within 10 km of two nearby emission facilities (Antelope Valley and Dakota Gasification Company), site-specific meteorological data at the DGC#12 site (10-m level data in a low-cut grassy field in the location shown in Figure 1), and hourly emissions data from 15 point sources. The terrain in the area is rolling and features three of the monitors (Beulah, DGC#16, and especially DGC#17) being above or close to stack top for some of the nearby emission sources; see Figure 2 for more close-up terrain details. Figure 1 shows a layout of the sources, monitors, and the meteorological station. Tables 2 and 3 provide details about the emission sources and the monitors. Although this modeling application employed sources as far away as 50 km, the proximity of the monitors to the two nearby emission facilities meant that emissions from those facilities dominated the impacts. However, to avoid criticism from reviewers that other regional sources that

Table 1. Databases selected for the model evaluation.

	Mercer County, North Dakota	Gibson Generating Station, Indiana
Number of emission sources modeled	15	5
Number of SO_2 monitors	5 (one above stack top for several sources)	4 (all below stack top)
Type of terrain	Rolling	Flat
Meteorological years and data source	2007–2010 Local 10-m tower data	2008–2010 Evansville airport
Meteorological data time step	Hourly and sub-hourly	Hourly and sub-hourly
Emissions and exhaust data	Actual hourly variable emissions and velocity, fixed temperature	Actual hourly variable emissions and velocity, fixed temperature

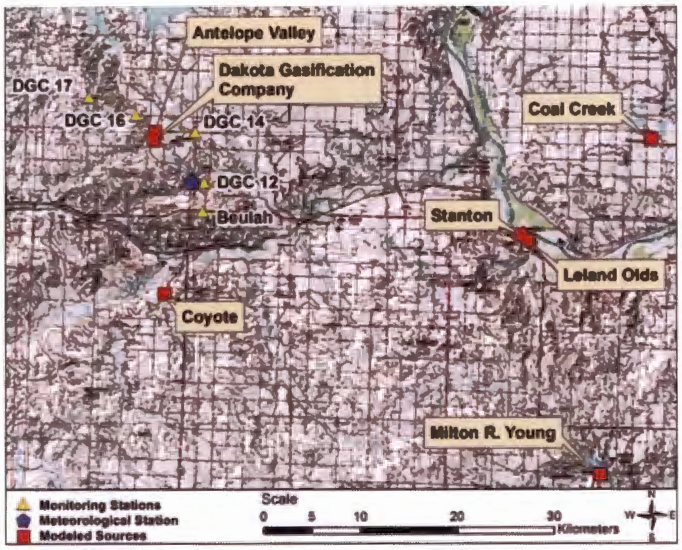

Figure 1. Map of North Dakota model evaluation layout.

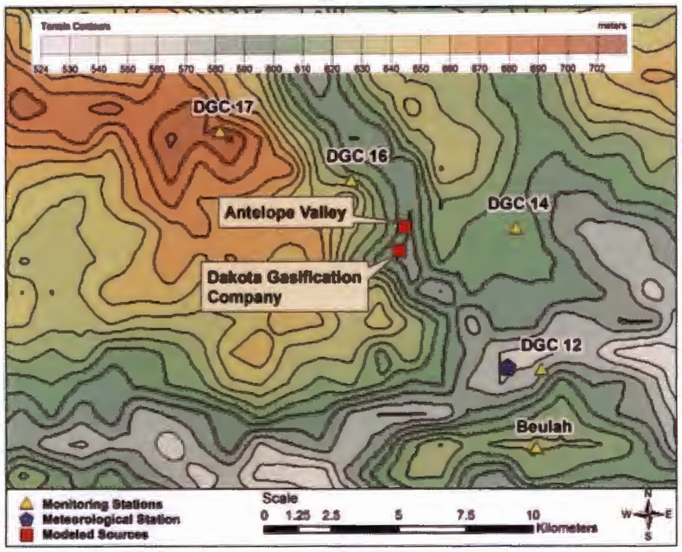

Figure 2. Terrain around the North Dakota monitors.

should have been modeled were omitted, other regional lignite-fired power plants were included in the modeling.

Gibson Generating Station, Indiana. An available 3-year period of 2008–2010 was used for the Gibson Generating Station in southwest Indiana with four SO_2 monitors within 6 km of the plant, airport hourly meteorological data (from Evansville, IN, 1-min data, located about 40 km SSE of the plant), and hourly emissions data from one electrical generating station (Gibson). The terrain in the area is quite flat and the stacks are tall. Figure 3 depicts the locations of the emission source and the four SO_2 monitors. Although the plant had an on-site meteorological tower, EPA (2013a) noted that the tower's location next to a large lake resulted in nonrepresentative boundary-layer conditions for the area, and that the use of airport data would be preferred. Tables 2 and 3 provide details about the emission sources and the monitors. Due to the fact that there are no major SO_2 sources within at least 30 km of Gibson, we modeled emissions from only that plant.

Meteorological Data Processing

For the North Dakota and Gibson database evaluations, the hourly surface meteorological data were processed with AERMET, the meteorological preprocessor for AERMOD. The boundary layer parameters were developed according to the guidance provided by EPA in the current AERMOD Implementation Guide (EPA, 2009). For the first modeling evaluation option, Test Case 1, AERMET was run using the default options. For the other four model evaluation options, Test Cases 2 to 5, AERMET was run with the beta u_* low wind speed option.

North Dakota meteorological processing

Four years (2007–2010) of the 10-m meteorological data collected at the DGC#12 monitoring station (located about 7 km SSE of the central emission sources) were processed with AERMET. The data measured at this monitoring station were wind direction, wind speed, and temperature. Hourly cloud

Table 2. Source information.

Database	Source ID	UTM X (m)	UTM Y (m)	Base elevation (m)	Stack height (m)	Exit temperature (K)	Stack diameter (m)
ND	Antelope Valley	285920	5250189	588.3	182.9	Vary	7.0
ND	Antelope Valley	285924	5250293	588.3	182.9	Vary	7.0
ND	Leland Olds	324461	5239045	518.3	106.7	Vary	5.3
ND	Leland Olds	324557	5238972	518.3	152.4	Vary	6.7
ND	Milton R Young	331870	5214952	597.4	171.9	Vary	6.2
ND	Milton R Young	331833	5214891	600.5	167.6	Vary	9.1
ND	Coyote	286875	5233589	556.9	151.8	Vary	6.4
ND	Stanton	323642	5239607	518.2	77.7	Vary	4.6
ND	Coal Creek	337120	5249480	602.0	201.2	Vary	6.7
ND	Coal Creek	337220	5249490	602.0	201.2	Vary	6.7
ND	Dakota Gasification Company	285552	5249268	588.3	119.8	Vary	7.0
ND	Dakota Gasification Company	285648	5249553	588.3	68.6	Vary	0.5
ND	Dakota Gasification Company	285850	5248600	588.3	76.2	Vary	1.0
ND	Dakota Gasification Company	285653	5249502	588.3	30.5	Vary	0.5
Gibson	Gibson 1	432999	4247189	119.0	189.0	327.2	7.6
Gibson	Gibson 2	432999	4247189	119.0	189.0	327.2	7.6
Gibson	Gibson 3	432923	4247251	118.5	189.0	327.2	7.6
Gibson	Gibson 4	432886	4247340	117.9	152.4	327.2	7.2
Gibson	Gibson 5	432831	4247423	116.3	152.4	327.2	7.2

Notes: SO_2 emission rate and exit velocity vary on hourly basis for each modeled source. Exit temperature varies by hour for the ND sources. UTM zones are 14 for North Dakota and 16 for Gibson.

Table 3. Monitor locations.

Database	Monitor	UTM X (m)	UTM Y (m)	Monitor elevation (m)
ND	DGC#12	291011	5244991	593.2
ND	DGC#14	290063	5250217	604.0
ND	DGC#16	283924	5252004	629.1
ND	DGC#17[a]	279025	5253844	709.8
ND	Beulah	290823	5242062	627.1
Gibson	Mt. Carmel	432424	4250202	119.0
Gibson	East Mt. Carmel	434654	4249666	119.3
Gibson	Shrodt	427175	4247182	138.0
Gibson	Gibson Tower	434792	4246296	119.0

Note: [a]This monitor's elevation is above stack top for several of the ND sources.

cover data from the Dickinson Theodore Roosevelt Regional Airport, North Dakota (KDIK) ASOS station (85 km to the SW), were used in conjunction with the monitoring station data. Upper air data were obtained from the Bismarck Airport, North Dakota (KBIS; about 100 km to the SE), twice-daily soundings.

In addition, the sub-hourly (10-min average) 10-m meteorological data collected at the DGC#12 monitoring station were also processed with AERMET. AERMET was set up to read six 10-min average files with the tower data and output six 10-min average surface and profile files for use in SHARP. SHARP then used the sub-hourly output of AERMET to calculate hourly modeled concentrations, without changing the internal computations of AERMOD. The SHARP user's manual (EPRI, 2013) provides detailed instructions on processing sub-hourly meteorological data and executing SHARP.

Gibson meteorological processing

Three years (2008–2010) of hourly surface data from the Evansville Airport, Indiana (KEVV), ASOS station (about 40 km SSE of Gibson) were used in conjunction with the

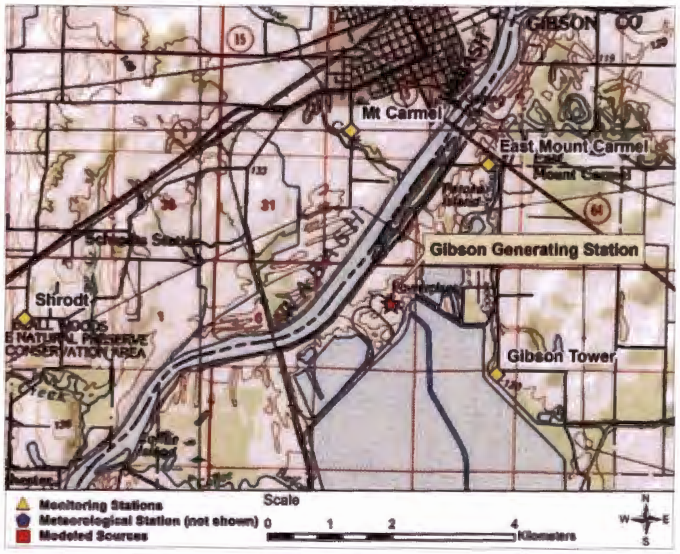

Figure 3. Map of Gibson model evaluation layout.

twice-daily soundings upper air data from the Lincoln Airport, Illinois (KILX, about 240 km NW of Gibson). The 10-min sub-hourly data for SHARP were generated from the 1-min meteorological data collected at Evansville Airport.

Emission Source Characteristics

Table 2 summarizes the stack parameters and locations of the modeled sources for the North Dakota and Gibson databases. Actual hourly emission rates, stack temperatures, and stack gas exit velocities were used for both databases.

Model Runs and Processing

For each evaluation database, the candidate model configurations were run with hourly emission rates provided by the plant operators. In the case of rapidly varying emissions (startup and shutdown), the hourly averages may average intermittent conditions occurring during the course of the hour. Actual stack heights were used, along with building dimensions used as input to the models tested. Receptors were placed only at the location of each monitor to match the number of observed and predicted concentrations.

The monitor (receptor) locations and elevations are listed in Table 3. For the North Dakota database, the DGC#17 monitor is located in the most elevated terrain of all monitors. The monitors for the Gibson database were located at elevations at or near stack base, with stack heights ranging from 152 to 189 m.

Tolerance Range for Modeling Results

One issue to be aware of regarding SO_2 monitored observations is that they can exhibit over- or underprediction tendencies up to 10% and still be acceptable. This is related to the tolerance in the EPA procedures (EPA, 2013b) associated with quality control checks and span checks of ambient measurements. Therefore, even ignoring uncertainties in model input parameters and other contributions (e.g., model science errors and random variations) that can also lead to modeling uncertainties, just the uncertainty in measurements indicates that modeled-to-monitored ratios between 0.9 and 1.1 can be considered "unbiased." In the discussion that follows, we consider model performance to be "relatively unbiased" if its predicted model to monitor ratio is between 0.75 and 1.25.

Model Evaluation Metrics

The model evaluation employed metrics that address three basic areas, as described next.

The 1-hr SO_2 NAAQS design concentration

An operational metric that is tied to the form of the 1-hour SO_2 National Ambient Air Quality Standards (NAAQS) is the "design concentration" (99th percentile of the peak daily 1-hr maximum values). This tabulated statistic was developed for each modeled case and for each individual monitor for each database evaluated.

Quantile–quantile plots

Operational performance of models for predicting compliance with air quality regulations, especially those involving a peak or near-peak value at some unspecified time and location, can be assessed with quantile–quantile (Q-Q) plots (Chambers et al., 1983), which are widely used in AERMOD evaluations. Q-Q plots are created by independently ranking (from largest to smallest) the predicted and the observed concentrations from a set of predictions initially paired in time and space. A robust model would have all points on the diagonal (45-degree) line. Such plots are useful for answering the question, "Over a period of time evaluated, does the distribution of the model predictions match those of observations?" Therefore, the Q-Q plot instead of the scatterplot is a pragmatic procedure for demonstrating model performance of applied models, and it is widely used by EPA (e.g., Perry et al. 2005). Venkatram et al. (2001) support the use of Q-Q plots for evaluating regulatory models. Several Q-Q plots are included in this paper in the discussion provided in the following.

Meteorological conditions associated with peak observed versus modeled concentrations

Lists of the meteorological conditions and hours/dates of the top several predictions and observations provide an indication as to whether these conditions are consistent between the model and monitoring data. For example, if the peak observed concentrations generally occur during daytime hours, we would expect that a well-performing model would indicate that the peak predictions are during the daytime as well. Another meteorological variable of interest is the wind speed magnitudes associated with observations and predictions. It would be expected, for example, that if the wind speeds associated with peak observations are low, then the modeled peak predicted hours would have the same characteristics. A brief qualitative summary of this analysis is included in this paper, and supplemental files contain the tables of the top 25 (unpaired) predictions and observations for all monitors and cases tested.

North Dakota Database Model Evaluation Procedures and Results

AERMOD was run for five test cases to compute the 1-hr daily maximum 99th percentile averaged over 4 years at the five ambient monitoring locations listed in Table 3. A regional background of 10 $\mu g/m^3$ was added to the AERMOD modeled predictions. The 1-hr 99th percentile background concentration was computed from the 2007–2010 lowest hourly monitored concentration among the five monitors so as to avoid double-counting impacts from sources already being modeled.

The ratios of the modeled (including the background of 10$\mu g/m^3$) to monitored design concentrations are summarized in

Table 4. North Dakota ratio of monitored to modeled design concentrations.

Test case	Monitor	Observed	Predicted	Ratio
Test Case 1	DGC#12	91.52	109.96	1.20
(Default AERMET, Default	DGC#14	95.00	116.84	1.23
AERMOD)	DGC#16	79.58	119.94	1.51
	DGC#17	83.76	184.48	2.20
	Beulah	93.37	119.23	1.28
Test Case 2	DGC#12	91.52	109.96	1.20
(Beta AERMET, Default	DGC#14	95.00	116.84	1.23
AERMOD)	DGC#16	79.58	119.94	1.51
	DGC#17	83.76	127.93	1.53
	Beulah	93.37	119.23	1.28
Test Case 3	DGC#12	91.52	103.14	1.13
(Beta AERMET, AERMOD with	DGC#14	95.00	110.17	1.16
LOWWIND2 σ_v = 0.3 m/sec)	DGC#16	79.58	111.74	1.40
	DGC#17	83.76	108.69	1.30
	Beulah	93.37	106.05	1.14
Test Case 4	DGC#12	91.52	95.86	1.05
(Beta AERMET, AERMOD with	DGC#14	95.00	100.50	1.06
LOWWIND2 σ_v = 0.5 m/sec)	DGC#16	79.58	106.65	1.34
	DGC#17	83.76	101.84	1.22
	Beulah	93.37	92.32	0.99
Test Case 5	DGC#12	91.52	82.18	0.90
(SHARP)	DGC#14	95.00	84.24	0.89
	DGC#16	79.58	95.47	1.20
	DGC#17	83.76	88.60	1.06
	Beulah	93.37	86.98	0.93

Notes: *Design concentration: 99th percentile peak daily 1-hr maximum, averaged over the years modeled and monitored.

Table 4 and graphically plotted in Figure 4 and are generally greater than 1. (Note that the background concentration is a small fraction of the total concentration, as shown in Table 4.) For the monitors in simple terrain (DGC#12, DGC#14, and Beulah), the evaluation results are similar for both the default and beta options and are within 5–30% of the monitored concentrations depending on the model option. The evaluation result for the monitor in the highest terrain (DGC#17) shows that the ratio of modeled to monitored concentration is more than 2, but when this location is modeled with the AERMET and AERMOD low wind beta options, the ratio is significantly better, at less than 1.3. It is noteworthy that the modeling results for inclusion of just the beta u_* option are virtually identical to the default AERMET run for the simple terrain monitors, but the differences are significant for the higher terrain monitor (DGC#17). For all of the monitors, it is evident that further reductions of AERMOD's overpredictions occur as the minimum σ_v in AERMOD is increased from 0.3 to 0.5 m/sec. For a minimum σ_v of 0.5 m/sec at all the monitors, AERMOD is shown to be conservative with respect to the design concentration.

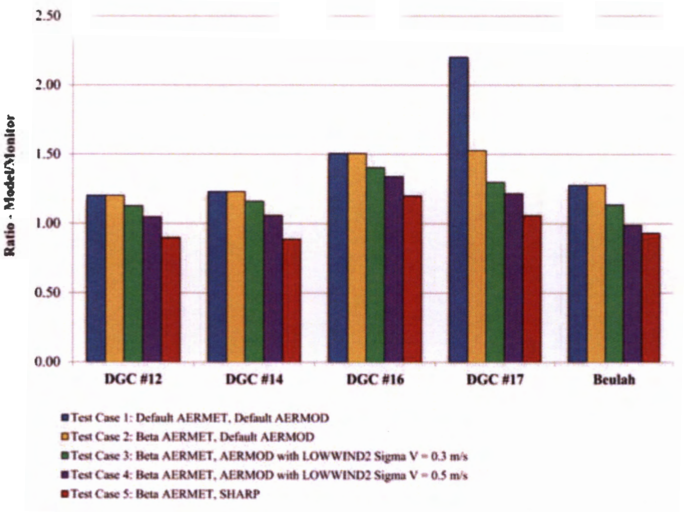

Figure 4. North Dakota ratio of monitored to modeled design concentration values at specific monitors.

The Q-Q plots of the ranked top fifty daily maximum 1-hr SO_2 concentrations for predictions and observations are shown in Figure 5. For the convenience of the reader, a vertical dashed line is included in each Q-Q plot to indicate the observed design concentration. In general, the Q-Q plots indicate the following:

- For all of the monitors, to the left of the design concentration line, the AERMOD hourly runs all show ranked predictions at or higher than observations. To the right of the design concentration line, the ranked modeled values for specific

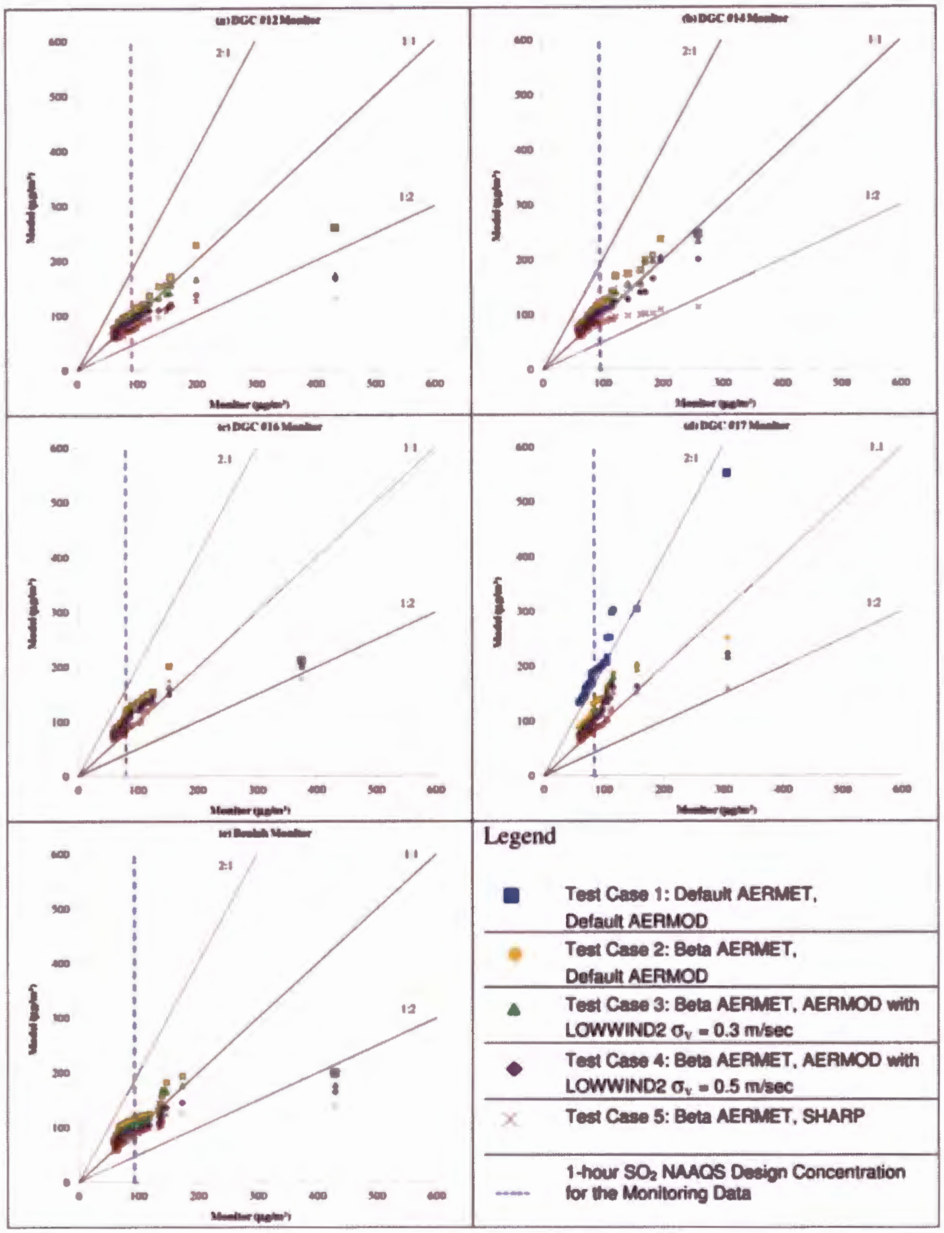

Figure 5. North Dakota Q-Q plots: top 50 daily maximum 1-hr SO_2 concentrations: (a) DGC #12 Monitor. (b) DGC#14 monitor. (c) DGC#16 monitor. (d) DGC#17 monitor. (e) Beulah monitor.

test cases and monitors are lower than the ranked observed levels, and the slope of the line formed by the plotted points is less than the slope of the 1:1 line. For model performance goals that would need to predict well for the peak concentrations (rather than the 99th percentile statistic), this area of the Q-Q plots would be of greater importance.

- The very highest observed value (if indeed valid) is not matched by any of the models for all of the monitors, but since the focus is on the 99th percentile form of the United States ambient standard for SO_2, this area of model performance is not important for this application.
- The ranked SHARP modeling results are lower than all of the hourly AERMOD runs, but at the design concentration level, they are, on average, relatively unbiased over all of the monitors. The AERMOD runs for SHARP included the meander component, which probably contributed to the small underpredictions noted for SHARP. In future modeling, we would advise users of SHARP to employ the AERMOD LOWWIND1 option to disable the meander component.

Gibson Generating Station Database Model Evaluation Procedures and Results

AERMOD was run for five test cases for this database as well in order to compute the 1-hr daily maximum 99th percentile averaged over three years at the four ambient monitoring locations listed in Table 3. A regional background of 18 μg/m^3 was added to the AERMOD modeled predictions. The 1-hr 99th percentile background concentration was computed from the 2008–2010 lowest hourly monitored concentration among the four monitors so as to avoid impacts from sources being modeled.

The ratio of the modeled (including the background of 18 μg/m^3) to monitored concentrations is summarized in Table 5 and graphically plotted in Figure 6 and are generally greater than 1.0. (Note that the background concentration is a small fraction of the total concentration, as shown in Table 5.) Figure 6 shows that AERMOD with hourly averaged meteorological data overpredicts by about 40–50% at Mt. Carmel and Gibson Tower monitors and by about 9–31% at East Mt. Carmel and Shrodt monitors. As expected (due to dominance of impacts with convective conditions), the AERMOD results do not vary much with the various low wind speed options in this flat terrain setting. AERMOD with sub-hourly meteorological data (SHARP) has the best (least biased predicted-to-observed ratio of design concentrations) performance among the five cases modeled. Over the four monitors, the range of predicted-to-observed ratios for SHARP is a narrow one, ranging from a slight underprediction by 2% to an overprediction by 14%.

The Q-Q plots of the ranked top fifty daily maximum 1-hr SO_2 concentrations for predictions and observations are shown in Figure 7. It is clear from these plots that the SHARP results parallel and are closer to the 1:1 line for a larger portion of the concentration range than any other model tested. In general, AERMOD modeling with hourly data exhibits an overprediction tendency at all of the monitors for the peak ranked concentrations at most of the monitors. The AERMOD/SHARP models predicted lower relative to observations at the East Mt. Carmel monitor for the very highest values, but match well for the 99th percentile peak daily 1-hr maximum statistic.

Evaluation Results Discussion

The modeling results for these tall stack releases are sensitive to the source local setting and proximity to complex terrain. In general, for tall stacks in simple terrain, the peak ground-level impacts mostly occur in daytime convective conditions. For settings with a mixture of simple and complex terrain, the peak impacts for the higher terrain are observed to occur during both daytime and nighttime conditions, while AERMOD tends to favor stable conditions only without low wind speed enhancements. Exceptions to this "rule of thumb" can occur for stacks with aerodynamic building downwash effects. In that case, high observed and modeled predictions are likely to occur during high wind events during all times of day.

The significance of the changes in model performance for tall stacks (using a 90th percentile confidence interval) was independently tested for a similar model evaluation conducted for Eastman Chemical Company (Paine et al., 2013; Szembek et al., 2013), using a modification of the Model Evaluation Methodology (MEM) software that computed estimates of the hourly stability class (Strimaitis et al., 1993). That study indicated that relative to a perfect model, a model that

Table 5. Gibson ratio of monitored to modeled design concentrations*.

Test case	Monitor	Observed	Predicted	Ratio
Test Case 1	Mt. Carmel	197.25	278.45	1.41
(Default AERMET, Default	East Mt. Carmel	206.89	230.74	1.12
AERMOD)	Shrodt	148.16	189.63	1.28
	Gibson Tower	127.12	193.71	1.52
Test Case 2	Mt. Carmel	197.25	287.16	1.46
(Beta AERMET, Default	East Mt. Carmel	206.89	229.22	1.11
AERMOD)	Shrodt	148.16	189.63	1.28
	Gibson Tower	127.12	193.71	1.52
Test Case 3	Mt. Carmel	197.25	280.32	1.42
(Beta AERMET, AERMOD with	East Mt. Carmel	206.89	224.65	1.09
LOWWIND2 σ_v = 0.3 m/sec)	Shrodt	148.16	184.82	1.25
	Gibson Tower	127.12	192.22	1.51
Test Case 4	Mt. Carmel	197.25	277.57	1.41
(Beta AERMET, AERMOD with	East Mt. Carmel	206.89	224.65	1.09
LOWWIND2 σ_v = 0.5 m/sec)	Shrodt	148.16	176.81	1.19
	Gibson Tower	127.12	192.22	1.51
Test Case 5	Mt. Carmel	197.25	225.05	1.14
(SHARP)	East Mt. Carmel	206.89	202.82	0.98
	Shrodt	148.16	136.41	0.92
	Gibson Tower	127.12	148.64	1.17

Notes: *Design Concentration: 99th percentile peak daily 1-hr maximum, averaged over the years modeled and monitored.

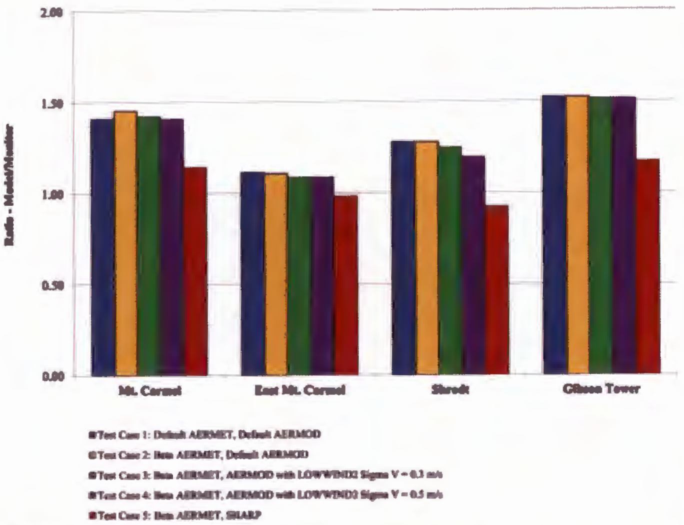

Figure 6. Gibson ratio of monitored to modeled design concentration values at specific monitors.

overpredicted or underpredicted by less than about 50% would likely show a performance level that was not significantly different. For a larger difference in bias, one could expect a statistically significant difference in model performance. This finding has been adopted as an indicator of the significance of different modeling results for this study.

A review of the North Dakota ratios of monitored to modeled values in Figure 4 generally indicates that for DGC#12, DGC#14, and Beulah, the model differences were not significantly different. For DGC#16, it could be concluded that the SHARP results were significantly better than the default AERMOD results, but other AERMOD variations were not significantly better. For the high terrain monitor, DGC#17, it is evident that all of the model options departing from default were significantly better than the default option, especially the SHARP approach.

For the Gibson monitors (see Figure 6), the model variations did not result in significantly different performance except for the Gibson Tower (SHARP vs. the hourly modes of running AERMOD).

General conclusions from the review of meteorological conditions associated with the top observed concentrations at the North Dakota monitors, provided in the supplemental file called "North Dakota Meteorological Conditions Resulting in Top 25 Concentrations," are as follows:

- A few peak observed concentrations occur at night with light winds. The majority of observations for the DGC#12 monitor are mostly daytime conditions with moderate to strong winds.
- Peak observations for the DGC#14 and Beulah monitors are mostly daytime conditions with a large range of wind speeds. Once again, a minority of the peak concentrations occur at night with a large range of wind speeds.

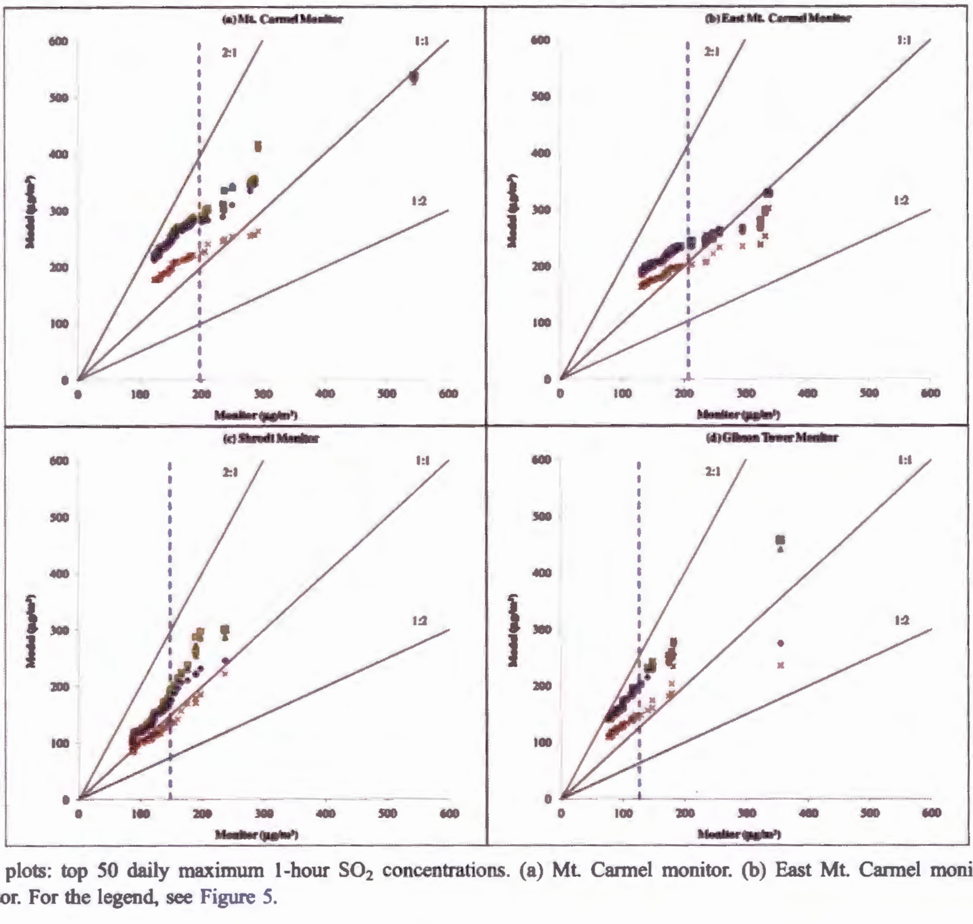

Figure 7. Gibson Q-Q plots: top 50 daily maximum 1-hour SO_2 concentrations. (a) Mt. Carmel monitor. (b) East Mt. Carmel monitor. (c) Shrodt monitor. (d) Gibson tower monitor. For the legend, see Figure 5.

- Peak observed concentrations for the DGC#16 and DGC#17 monitors occur at night with light winds. Majority of observations are mixed between daytime and nighttime conditions with a large range of wind speeds for both. The DGC#17 monitor is located in elevated terrain.

The conclusions from the review of the meteorological conditions associated with peak AERMOD or SHARP predictions are as follows:

- AERMOD hourly peak predictions for the DGC#12 and Beulah monitors are consistently during the daytime with light to moderate wind speeds and limited mixing heights. This is a commonly observed situation that is further discussed later.
- There are similar AERMOD results for DGC#14, except that there are more periods with high winds and higher mixing heights.
- The AERMOD results for DGC#16 still feature mostly daytime hours, but with more high wind conditions.
- The default AERMOD results for DGC#17 are distinctly different from the other monitors, with most hours featuring stable, light winds. There are also a few daytime hours of high predictions with low winds and low mixing heights. This pattern changes substantially with the beta u_* options employed, when the majority of the peak prediction hours are daytime periods with light to moderate wind speeds. This pattern is more consistent with the peak observed concentration conditions.
- The SHARP peak predictions at the North Dakota monitors were also mostly associated with daytime hours with a large range of wind speeds for all of the monitors.

The North Dakota site has some similarities due to a mixture of flat and elevated terrain to the Eastman Chemical Company model evaluation study in Kingsport, TN (this site features three coal-fired boiler houses with tall stacks). In that study (Paine et al. 2013; Szembek et al., 2013), there was one monitor in elevated terrain and two monitors in flat terrain with a full year of data. Both the North Dakota and Eastman sites featured observations of the design concentration being within about 10% of the mean design concentration over all monitors. Modeling results using default options in AERMOD for both of these sites indicated a large spread of the predictions, with predictions in high terrain exceeding observations by more than a factor of 2. In contrast, the predictions in flat terrain, while higher than observations, showed a lower overprediction bias. The use of low wind speed improvements in AERMOD (beta u_* in AERMET and an elevated minimum σ_v value) did improve model predictions for both databases.

The conclusions from the review of the meteorological conditions associated with peak observations, provided in the supplemental file called "Gibson Meteorological Conditions Resulting in Top 25 Concentrations," are as follows:

- Peak observations for the Mt. Carmel and East Mt. Carmel monitors occur during both light wind convective conditions and strong wind conditions (near neutral, both daytime and nighttime).
- Nighttime peaks that are noted at Mt. Carmel and East Mt. Carmel could be due to downwash effects with southerly winds.
- Gibson Tower and Shrodt monitors were in directions with minimal downwash effects; therefore, the peak impacts at these monitors occur with convective conditions.
- The Gibson Tower and Shrodt monitor peak observation conditions were similarly mixed for wind speeds, but they were consistently occurring during the daytime only.

AERMOD (hourly) modeling runs and SHARP runs are generally consistent with the patterns of observed conditions for Shrodt and Gibson Tower monitors. Except for downwash effects, the peak concentrations were all observed and predicted during daytime hours. There are similar AERMOD results for Mt. Carmel and East Mt. Carmel, except that there are more nighttime periods and periods with strong wind conditions.

As noted earlier, AERMOD tends to focus its peak predictions for tall stacks in simple terrain (those not affected by building downwash) for conditions with low mixing heights in the morning. However, a more detailed review of these conditions indicates that the high predictions are not simply due to plumes trapped within the convective mixed layer, but instead due to plumes that initially penetrate the mixing layer, but then emerge (after a short travel time) into the convective boundary layer in concentrated form with a larger-than-expected vertical spread. Tests of this condition were undertaken by Dr. Ken Rayner of the Western Australia Department of Environmental Regulation (2013), who found the same condition occurring for tall stacks in simple terrain for a field study database in his province. Rayner found that AERMOD tended to overpredict peak concentrations by a factor of about 50% at a key monitor, while with the penetrated plume removed from consideration, AERMOD would underpredict by about 30%. Therefore, the correct treatment might be a more delayed entrainment of the penetrated plume into the convective mixed layer. Rayner's basic conclusions were:

- A plume penetrates and disperses within a 1-hr time step in AERMOD, while in the real world, dispersion of a penetrated puff may occur an hour or more later, after substantial travel time.
- A penetrated plume initially disperses via a vertical Gaussian formula, not a convective probability density function. Because penetrated puffs typically have a very small vertical dispersion, they are typically fully entrained (in AERMOD) in a single hour by a growing mixed layer, and dispersion of a fully entrained puff is via convective mixing, with relatively rapid vertical dispersion, and high ground-level concentrations.

Conclusions and Recommendations for Further Research

This study has addressed additional evaluations for low wind conditions involving tall stack releases for which multiple years of concurrent emissions, meteorological data, and monitoring data were available. The modeling cases that were the focus of this study involved applications with only one level of meteorological data and no direct turbulence measurements or vertical temperature gradient observations.

For the North Dakota evaluation, the AERMOD model overpredicted, using the design concentration as the metric for each monitor. For the relatively low elevation monitors, the results were similar for both the default and beta options and are within 5–30% of the monitored concentrations depending on the model option. The modeling result for the elevated DGC#17 monitor showed that this location is sensitive to terrain, as the ratio of modeled to monitored concentration is over 2. However, when this location was modeled with the low wind beta option, the ratio was notably better, at less than 1.3. Furthermore, the low wind speed beta option changed the AERMOD's focus on peak predictions conditions from mostly nighttime to mostly daytime periods, somewhat more in line with observations. Even for a minimum σ_v as high as 0.5 m/sec, all of the AERMOD modeling results were conservative or relatively unbiased (for the design concentration). The North Dakota evaluation results for the sub-hourly (SHARP) modeling were, on average, relatively unbiased, with a predicted-to-observed design concentration ratio ranging from 0.89 to 1.2. With a 10% tolerance in the SO_2 monitored values, we find that the SHARP performance is quite good. Slightly higher SHARP predictions would be expected if AERMOD were run with the LOWWIND1 option deployed.

For the Gibson flat terrain evaluation, AERMOD with hourly averaged meteorological data overpredicted at three of the four monitors between 30 and 50%, and about 10% at the fourth monitor. The AERMOD results did not vary much with the various low wind speed options in this flat terrain setting. AERMOD with sub-hourly meteorological data (SHARP) had the best (least biased predicted-to-observed ratio of design concentrations) performance among the five cases modeled. Over the four monitors, the range of predicted-to-observed ratios for SHARP was a narrow one, ranging from a slight underprediction by 2% to an overprediction by 14%. All other modeling options had a larger range of results.

The overall findings with the low wind speed testing on these tall stack databases indicate that:

- The AERMOD low wind speed options have a minor effect for flat terrain locations.
- The AERMOD low wind speed options have a more significant effect with AERMOD modeling for elevated terrain locations, and the use of the LOWWIND2 option with a minimum σ_v on the order of 0.5 m/sec is appropriate.
- The AERMOD sub-hourly modeling (SHARP) results are mostly in the unbiased range (modeled to observed design concentration ratios between 0.9 and 1.1) for the two databases tested with that option.
- The AERMOD low wind speed options improve the consistency of meteorological conditions associated with the highest observed and predicted concentration events.

Further analysis of the low wind speed performance of AERMOD with either the SHARP procedure or the use of the minimum σ_v specifications by other investigators is encouraged. However, SHARP can only be used if sub-hourly meteorological data is available. For Automated Surface Observing Stations (ASOS) with 1-min data, this option is a possibility if the 1-min data are obtained and processed.

Although the SHARP results reported in this paper are encouraging, further testing is recommended to determine the optimal sub-hourly averaging time (no less than 10 min is recommended) and whether other adjustments to AERMOD (e.g., total disabling of the meander option) are recommended. Another way to implement the sub-hourly information in AERMOD and to avoid the laborious method of running AERMOD several times for SHARP would be to include a distribution, or range, of the sub-hourly wind directions to AERMOD so that the meander calculations could be refined.

For most modeling applications that use hourly averages of meteorological data with no knowledge of the sub-hourly wind distribution, it appears that the best options with the current AERMOD modeling system are to implement the AERMET beta u_* improvements and to use a minimum σ_v value on the order of 0.5 m/sec/sec.

It is noteworthy that EPA has recently approved (EPA, 2015) as a site-specific model for Eastman Chemical Company the use of the AERMET beta u_* option as well as the LOWWIND2 option in AERMOD with a minimum σ_v of 0.4 m/sec. This model, which was evaluated with site-specific meteorological data and four SO_2 monitors operated for 1 year, performed well in flat terrain, but overpredicted in elevated terrain, where a minimum σ_v value of 0.6 m/sec actually performed better. This would result in an average value of the minimum σ_v of about 0.5 m/sec, consistent with the findings of Hanna (1990).

The concept of a minimum horizontal wind fluctuation speed on the order of about 0.5 m/sec is further supported by the existence of vertical changes (shears) in wind direction (as noted by Etling, 1990) that can result in effective horizontal shearing of a plume that is not accounted for in AERMOD. Although we did not test this concept here, the concept of vertical wind shear effects, which are more prevalent in decoupled stable conditions than in well-mixed convective conditions, suggests that it would be helpful to have a "split minimum σ_v" approach in AERMOD that enables the user to specify separate minimum σ_v values for stable and unstable conditions. This capability would, of course, be backward-compatible to the current minimum σ_v specification that applies for all stability conditions in AERMOD now.

Supplemental Material

Supplemental data for this article can be accessed at the publisher's website

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Appendix C

Evaluation of Low Wind Modeling Approaches for Two Tall-Stack Databases with AERMET ADJ_U* and AERMOD LOWWIND3 Options

Evaluation of Low Wind Modeling Approaches for Two Tall-Stack Databases with AERMOD LOWWIND3 Option

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Complete List of Authors:	Samani, Olga; AECOM, Air Quality Paine, Robert; AECOM,
Keywords:	Modeling, LOWWIND3, AERMOD
Abstract:	The analysis documented in this paper addresses evaluations using a new AERMOD modeling option ("LOWWIND3") for low wind conditions made available by the US EPA in July 2015. These results are provided to update our previous published evaluation results using another AERMOD option ("LOWWIND2"). AERMOD was tested on the same two field study databases as before, involving tall stacks, several SO2 monitors, and hourly emissions data. Several technical options were tested: default mode for both AERMET (the meteorological pre-processor) and AERMOD (the dispersion model), as well as AERMET with an adjustment for computing the friction velocity and other planetary boundary layer parameters more accurately in low wind speed conditions ("ADJ_U*"). The new tests reported here also involved the use of the AERMOD dispersion model with the LOWWIND3 option that provides a higher minimum value for the standard deviation of the lateral wind speed component (sigma-v) than the default option provides. The field study databases included 1) Mercer County, a North Dakota database featuring five SO2 monitors within 10 kilometers of the Dakota Gasification Company's plant and the Antelope Valley Station power plant in an area of both flat and elevated terrain, and 2) a flat-terrain setting

	database with four SO2 monitors within 6 kilometers of the Gibson Generating Station in southwest Indiana. Both sites featured regionally representative 10-meter meteorological databases, with no significant terrain obstacles between the meteorological site and the emission sources. The newly available LOWWIND3 option shows results similar to the LOWWIND2 option, with slightly reduced over-predictions for both databases. As such, these evaluations indicate that use of the ADJ_U* with the LOWWIND3 option provides the best model performance among the options tested, while retaining a slight over-prediction bias.

Implications

AERMOD evaluations for two tall stack databases (in North Dakota and Indiana) in areas of both flat and elevated terrain were updated using the newly-released LOWWIND3 option. AERMOD runs with both the ADJ_U* and LOWWIND3 options showed improvement in model performance (especially in higher terrain areas) over the default options, helping to reduce some of the over-prediction biases currently present in regulatory default AERMOD while retaining a slight over-prediction bias.

Evaluation of Low Wind Modeling Approaches for Two Tall-Stack Databases with AERMOD LOWWIND3 Option

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Abstract

The analysis documented in this paper addresses evaluations using a new AERMOD modeling option ("LOWWIND3") for low wind conditions made available by the US EPA in July 2015. These results are provided to update our previous published evaluation results using another AERMOD option ("LOWWIND2").

AERMOD was tested on the same two field study databases as before, involving tall stacks, several SO_2 monitors, and hourly emissions data. Several technical options were tested: default mode for both AERMET (the meteorological pre-processor) and AERMOD (the dispersion model), as well as AERMET with an adjustment for computing the friction velocity and other planetary boundary layer parameters more accurately in low wind speed conditions ("ADJ_U*"). The new tests reported here also involved the use of the AERMOD dispersion model with the LOWWIND3 option that provides a higher minimum value for the standard deviation of the lateral wind speed component (sigma-v) than the default option provides.

The field study databases included 1) Mercer County, a North Dakota database featuring five SO_2 monitors within 10 kilometers of the Dakota Gasification Company's plant and the Antelope Valley Station power plant in an area of both flat and elevated terrain, and 2) a flat-terrain setting database with four SO_2 monitors within 6 kilometers of the Gibson Generating Station in southwest Indiana. Both sites featured regionally representative 10-meter meteorological databases, with no significant terrain obstacles between the meteorological site and the emission sources.

The newly available LOWWIND3 option shows results similar to the LOWWIND2 option, with slightly reduced over-predictions for both databases. As such, these evaluations indicate that use of the ADJ_U* with the LOWWIND3 option provides the best model performance among the options tested, while retaining a slight over-prediction bias.

Introduction

In a proposed rulemaking published in the July 29, 2015 Federal Register EPA (2015a), the United States Environmental Protection Agency (EPA) released a revised version of AERMOD (15181), which replaces AERMOD version 14134. EPA proposed refinements to its preferred short-range model, AERMOD, involving low wind conditions. These refinements involve an adjustment to the computation of the friction velocity ("ADJ_U*") in the AERMET meteorological pre-processor and a higher minimum lateral wind speed standard deviation, sigma-v (σ_v), as incorporated into the "LOWWIND3" option. The EPA proposal indicates that "the LOWWIND3 BETA option increases the minimum value of sigma-v from 0.2 to 0.3 m/s, uses the FASTALL approach to replicate the centerline concentration accounting for horizontal meander, but utilizes an effective sigma-y and eliminates upwind dispersion" EPA (2015b). These low wind AERMOD options continue to be regarded as experimental ("beta") options pending further evaluation and public comment.

Paine et al. (2015) described the evaluation of the combined ADJ_U* and LOWWIND2 options as implemented in AERMOD version 14134 on two tall-stack databases. Here we compare the EPA-proposed options (with LOWWIND2 replaced by LOWWIND3) on the same databases.

Modeling Options and Databases for Testing

The meteorological data, emissions, and receptors used in this analysis were identical to those used in the Paine et al. (2015) analysis. The test cases provided in this updated evaluation reported here are listed below, and use some of the results already reported by Paine et al. (2015).

Test Case 1: AERMET and AERMOD in default mode.
Test Case 2: Low wind beta option for AERMET and default options for AERMOD.
Test Case 3: Low wind beta option for AERMET and the LOWWIND2 option for AERMOD.
Test Case 4: Low wind beta option for AERMET and the LOWWIND3 option for AERMOD.

Both LOWWIND2 and LOWWIND3 as tested had a minimum σ_v value of 0.3 m/sec.

The Mercer County, North Dakota and Gibson Generating Station, Indiana databases were selected for the low wind model evaluation due to the following attributes:

- They feature multiple years of hourly SO_2 monitoring at several sites.
- Emissions are dominated by tall stack sources that are available from continuous emission monitors.
- There is representative meteorological data from a single-level station typical of (or obtained from) airport-type data.

North Dakota Database Model Evaluation Procedures and Results

AERMOD was run for the test cases listed above for the North Dakota databases to compute the 1-hour daily maximum 99th percentile averaged over four years at the five ambient monitoring locations (consistent with the United States 1-hour SO_2 ambient standard). A regional background of 10 $\mu g/m^3$ was added to the AERMOD modeled predictions, as determined from a review of rural monitors unaffected by local sources.

The predicted-to-observed ratios for the North Dakota evaluation database are graphically plotted in Figure 1. The evaluation results for the four test cases indicate that the predicted-to-observed ratios are consistently greater than 1.0 and AERMOD still over-predicts with use of the proposed ADJ_U* and the LOWWIND3 options. The results for the new model with low wind option (Test Case 4) are very close to the use of the LOWWIND2 option (Test Case 3). The low wind options show improvement relative to the default option at all monitors, especially the monitor in higher terrain (DGC #17). Supplemental file contains the tables and quantile-quantile plots of the top 50 (unpaired) predictions and observations for Test Case 1 and Test Case 4. Test Case 2 and Test Case 3 results were already reported by Paine et al.

Figure 1

Gibson Generating Station Database Model Evaluation Procedures and Results

AERMOD was evaluated with the four test cases described above to compute the 1-hour daily maximum 99th percentile averaged over three years at the four ambient monitors. A regional background of 18 $\mu g/m^3$ was added to the AERMOD modeled predictions.

The predicted-to-observed ratios are graphically plotted in Figure 2, and these ratios are consistently greater than 1.0. The EPA-proposed LOWWIND3 low wind option (Test Case 4) provided modest improvements in performance relative to the default option (Test Case 1), while still showing an over-prediction tendency at each monitor. Supplemental file contains the tables and quantile-quantile plots of the top 50 (unpaired) predictions and observations for Test Case 1 and Test Case 4. Test Case 2 and Test Case 3 results were already reported by Paine et al. (2015).

Figure 2

Conclusions

The model evaluation results for the new version of AERMOD (version 15181) on the two databases previously evaluated using an older version of AERMOD showed that the EPA-proposed low wind options (ADJ_U* and LOWWIND3) perform better than the default option, while still over-predicting the critical 99th percentile concentration associated with the 1-hour SO_2 ambient standard at each monitor for both databases.

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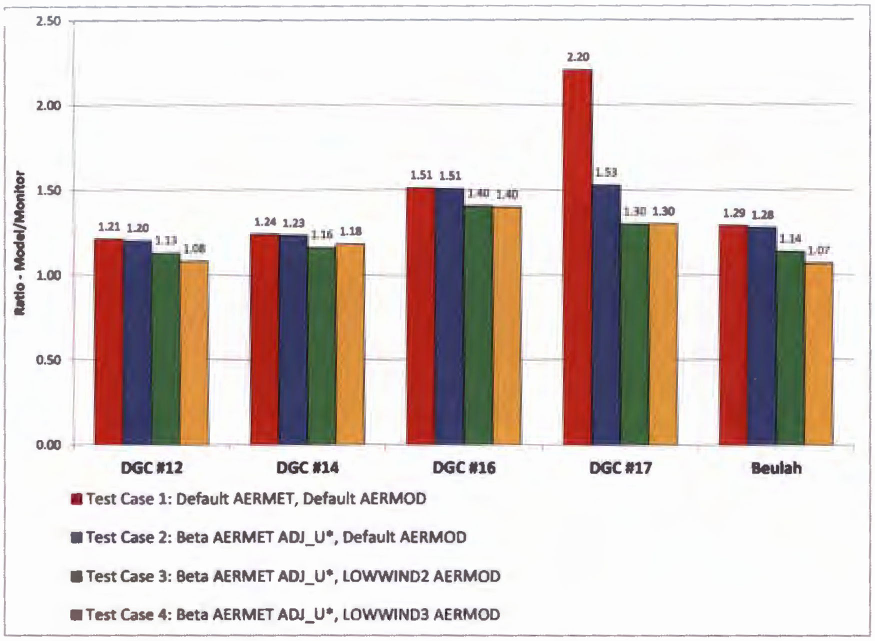


Figure 1. North Dakota Ratio of Monitored to Modeled Design Concentration Values at Specific Monitors
279x215mm (300 x 300 DPI)

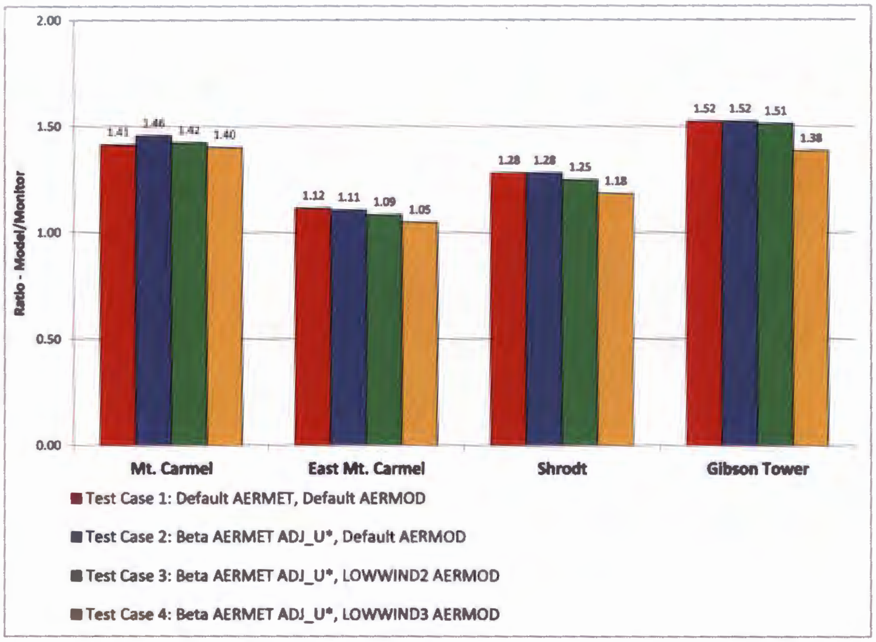
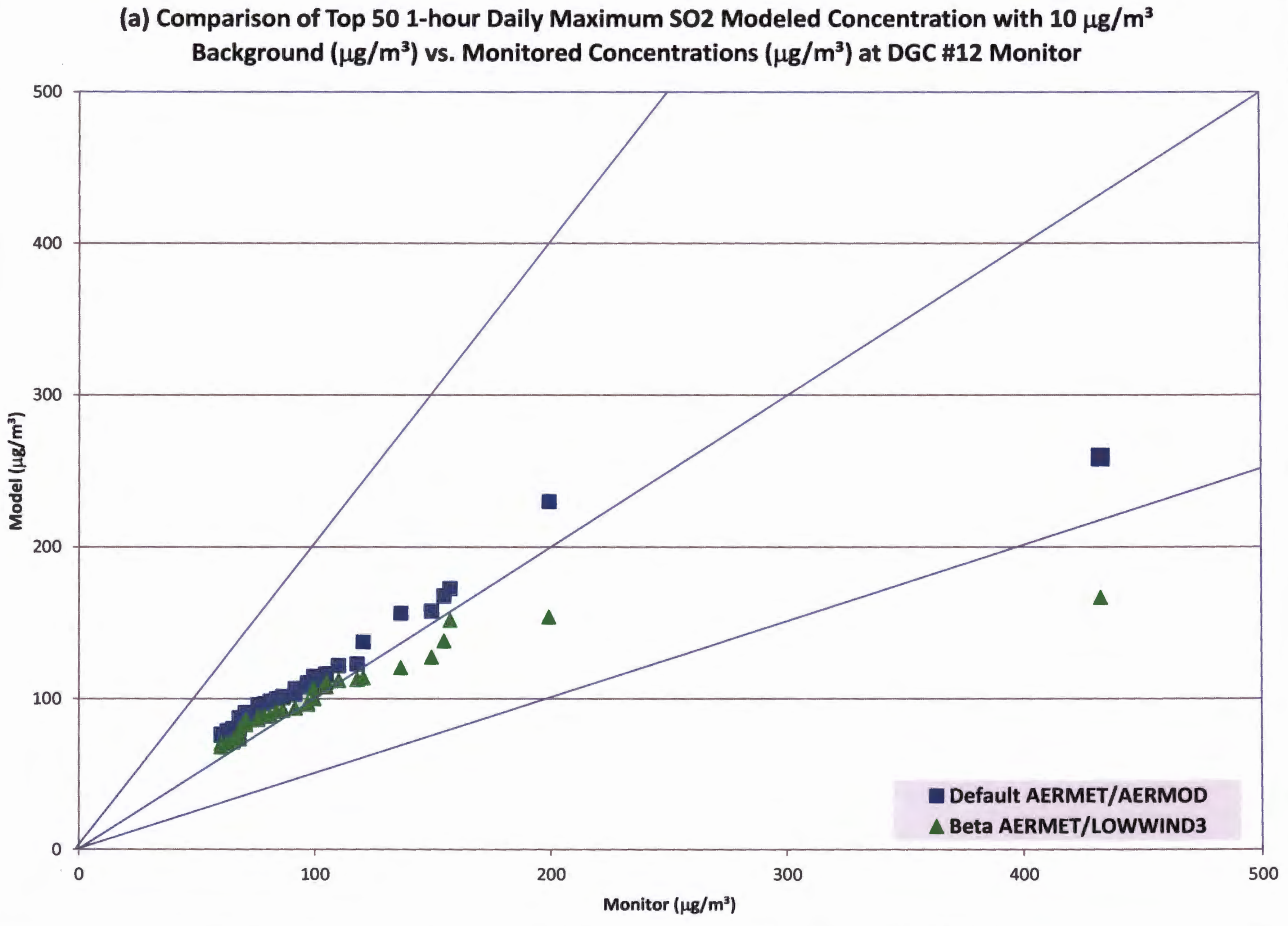


Figure 2. Gibson Ratio of Monitored to Modeled Design Concentration Values at Specific Monitors
279x215mm (300 x 300 DPI)

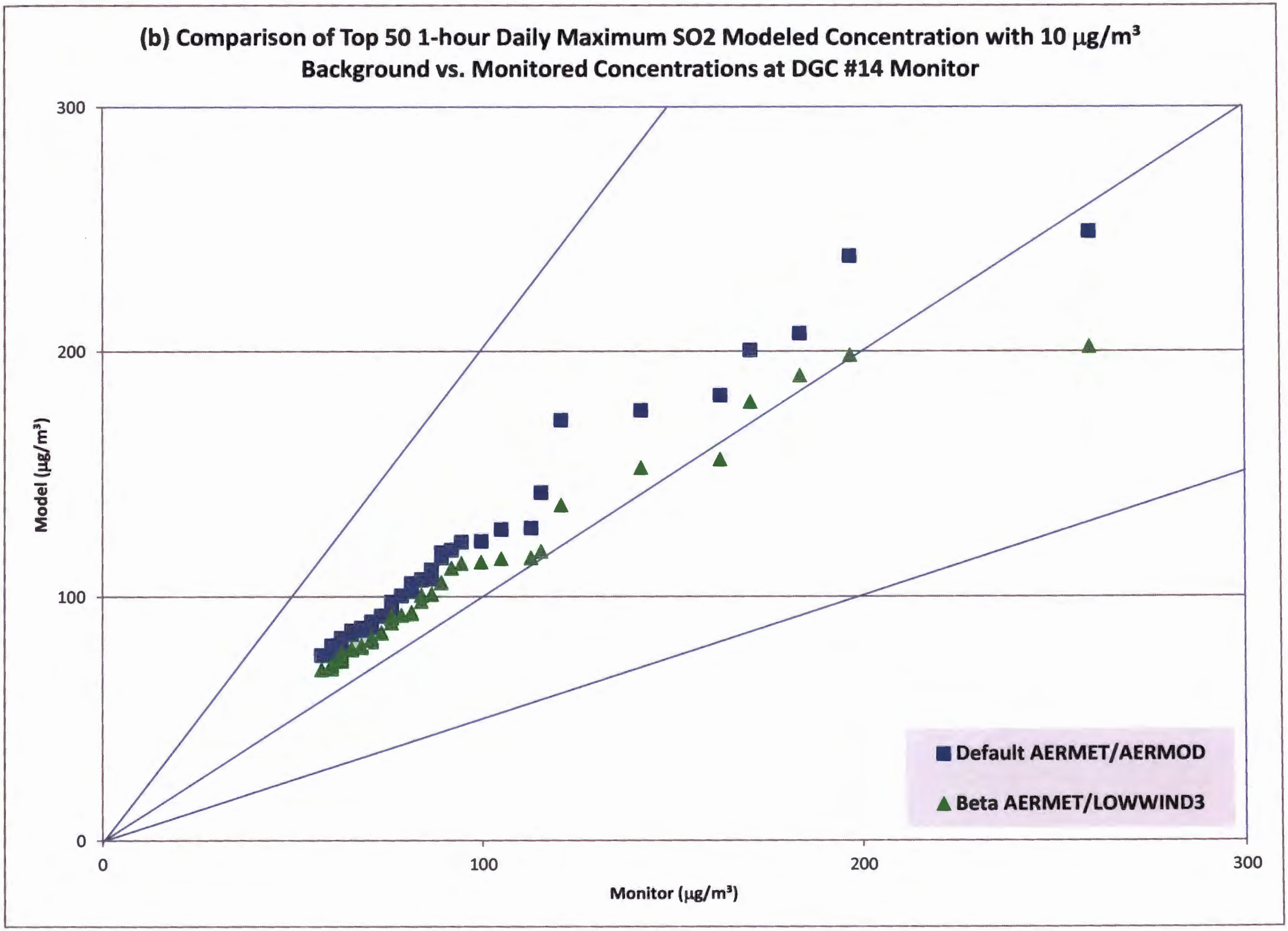
1. Figure 1. North Dakota Ratio of Monitored to Modeled Design Concentration Values at Specific Monitors
2. Figure 2. Gibson Ratio of Monitored to Modeled Design Concentration Values at Specific Monitors

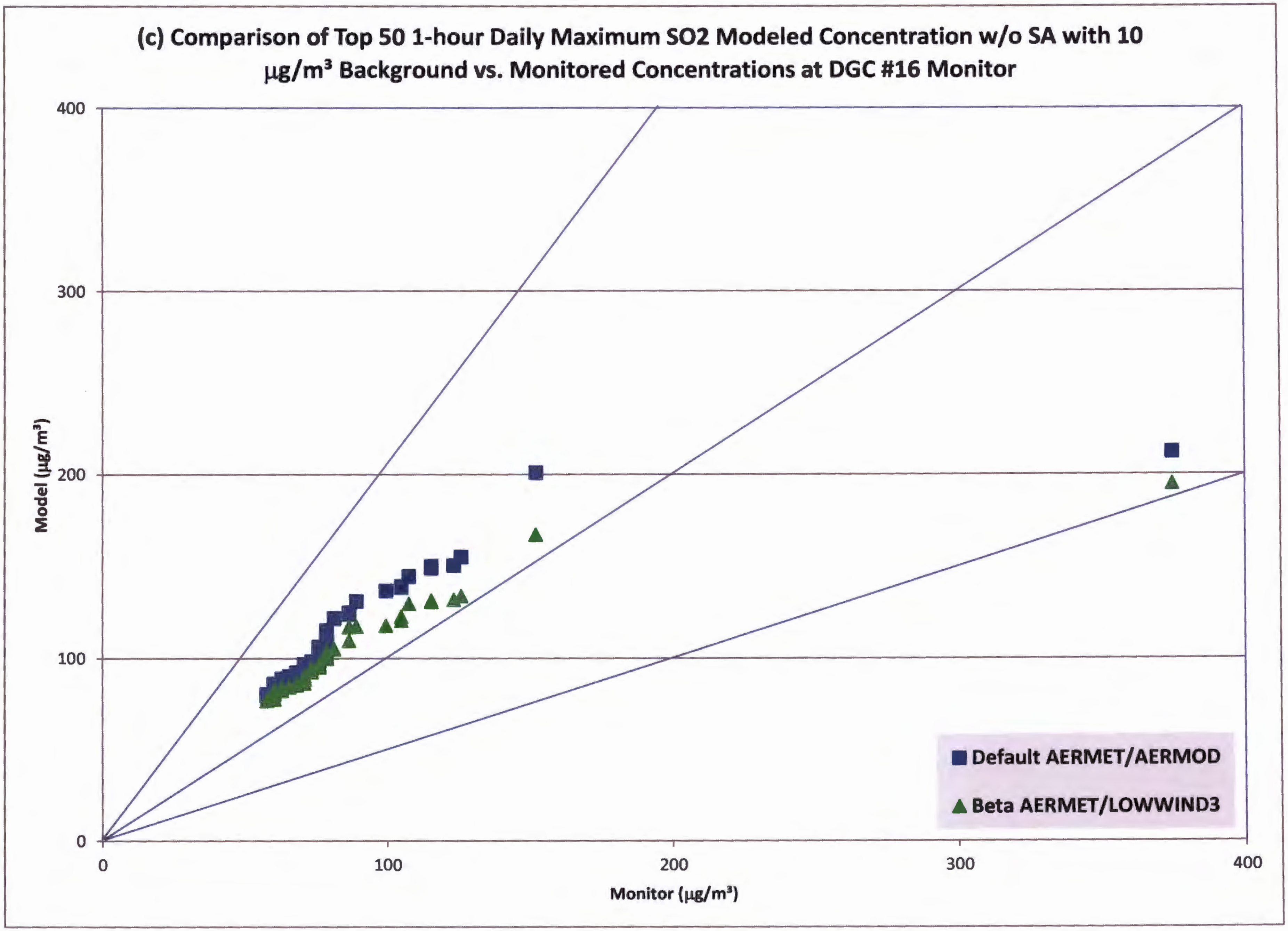
North Dakota: Top 50 1-hour SO2 Daily Max Monitoring and Predicted Concentrations

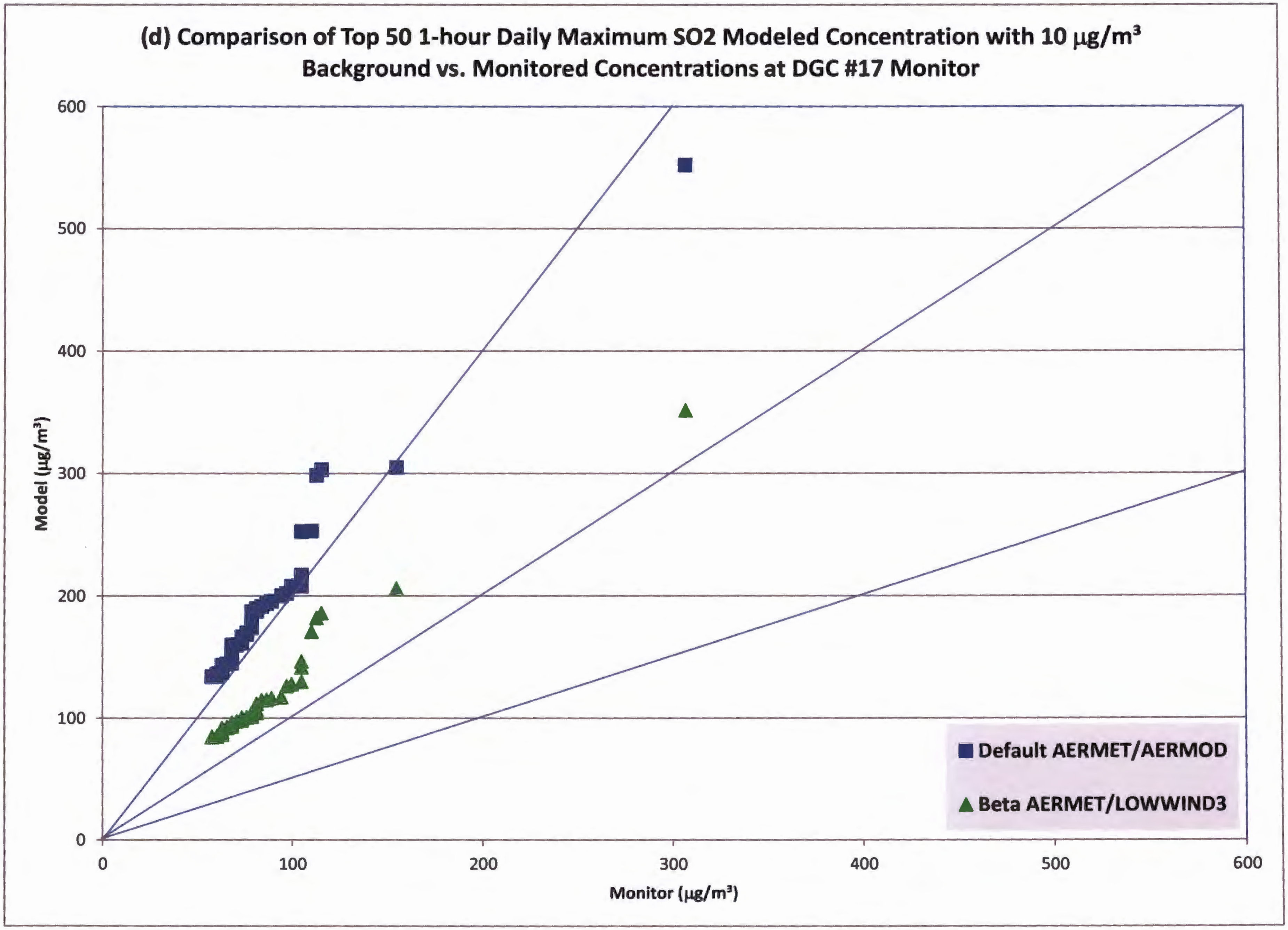
DGC12	DGC14	DGC16	DGC17	Beulah	DGC12	DGC14	DGC16	DGC17	Beulah	DGC12	DGC14	DGC16	DGC17	Beulah
Monitored					Default AERMET/AERMOD					Beta AERMET/LOWWIND3				
432.28	259.37	374.64	306.52	429.66	259.01	248.84	212.05	551.94	200.73	166.74	201.85	194.87	351.53	174.11
199.11	196.49	151.95	154.57	172.91	229.73	238.94	200.87	304.74	194.42	154.14	198.35	167.19	206.04	173.04
157.19	183.39	125.75	115.27	146.71	172.70	207.22	155.15	303.06	182.88	151.71	190.11	133.92	185.82	162.41
154.57	170.29	123.13	112.65	141.47	167.90	200.40	150.47	298.39	167.62	138.15	179.26	131.82	182.08	158.78
149.33	162.43	115.27	110.03	138.85	157.80	182.01	150.07	252.86	159.41	127.36	155.87	131.40	170.61	131.91
136.23	141.47	115.27	104.79	136.23	156.30	175.78	149.06	252.56	143.96	120.38	152.45	130.75	146.31	131.00
120.51	120.51	107.41	104.79	136.23	137.49	171.87	144.49	217.09	136.07	113.69	137.24	129.71	141.65	125.14
117.89	115.27	104.79	104.79	133.61	122.95	142.37	139.13	207.90	131.34	112.55	118.38	122.71	129.70	118.79
110.03	112.65	104.79	99.55	117.89	121.89	128.02	138.50	207.88	126.99	112.03	115.74	120.53	127.77	116.34
110.03	104.79	99.55	96.93	115.27	121.85	127.34	136.66	202.01	125.58	111.89	115.45	117.65	126.34	113.08
104.79	99.55	89.08	94.31	110.03	116.27	122.63	131.00	200.13	125.02	110.77	114.05	117.29	117.17	111.73
104.79	94.31	86.46	89.08	107.41	115.54	122.25	124.74	195.49	123.38	107.65	113.47	117.05	116.36	110.95
99.55	91.70	86.46	86.46	104.79	114.72	118.94	124.08	193.71	122.51	106.49	111.57	109.56	114.90	110.48
99.55	89.08	81.22	83.84	99.55	113.13	117.93	121.73	191.25	120.89	100.45	105.72	105.07	114.63	110.20
99.55	89.08	78.60	81.22	99.55	110.86	115.83	115.10	189.60	118.51	99.86	105.67	103.42	111.62	108.71
96.93	86.46	78.60	81.22	91.70	110.37	110.88	114.81	188.90	115.61	97.40	100.99	102.78	107.06	108.43
96.93	86.46	78.60	81.22	91.70	107.84	107.29	109.31	188.18	115.40	96.06	100.83	102.43	104.39	106.84
91.70	83.84	78.60	81.22	83.84	106.55	107.03	109.02	187.51	113.99	93.90	100.55	101.12	104.06	105.18
91.70	83.84	78.60	78.60	83.84	105.59	106.84	108.73	187.13	112.11	93.78	98.07	99.78	103.94	104.57
91.70	81.22	75.98	78.60	81.22	102.74	105.44	106.19	183.14	110.71	93.46	93.56	96.96	103.59	99.57
86.46	81.22	75.98	78.60	81.22	101.42	102.13	105.41	180.84	110.22	92.44	93.02	96.86	101.99	97.61
86.46	78.60	75.98	78.60	78.60	100.91	100.44	103.18	176.71	109.35	92.33	92.35	96.05	101.27	96.86
83.84	75.98	75.98	78.60	78.60	99.91	97.86	102.59	173.95	108.13	91.54	92.00	95.28	101.00	96.17
81.22	75.98	75.98	75.98	73.36	98.30	95.78	99.84	169.81	107.74	88.78	91.95	95.26	100.71	93.94
81.22	75.98	75.98	75.98	73.36	98.12	94.48	98.56	168.47	105.48	88.69	91.22	94.99	100.49	93.78
78.60	75.98	73.36	73.36	70.74	96.61	93.19	98.26	166.45	103.44	88.40	89.23	94.55	100.43	91.74
75.98	73.36	73.36	73.36	70.74	95.84	92.18	97.30	166.44	103.15	87.88	85.37	92.45	99.59	90.97
75.98	73.36	70.74	73.36	70.74	93.29	92.08	96.78	165.91	102.19	87.09	85.14	90.53	98.99	90.39
75.98	70.74	70.74	73.36	68.12	92.69	89.80	95.78	161.63	102.04	86.07	83.28	89.13	98.10	88.75
70.74	70.74	70.74	70.74	68.12	90.80	88.71	95.27	159.85	99.01	86.03	82.54	88.74	97.44	88.30
70.74	70.74	70.74	68.12	68.12	89.01	87.52	93.63	159.71	98.25	83.88	81.58	88.31	96.15	88.29
70.74	68.12	70.74	68.12	68.12	87.93	87.27	93.55	158.85	95.70	82.71	80.34	86.39	95.58	88.08
68.12	68.12	68.12	68.12	68.12	87.42	86.47	92.27	151.20	95.39	80.00	80.15	86.11	95.32	85.24
68.12	68.12	68.12	68.12	65.50	87.15	86.40	92.15	148.91	95.32	79.82	79.45	85.71	95.19	84.97
68.12	68.12	68.12	68.12	65.50	86.55	86.24	91.23	148.58	93.92	77.28	79.33	85.31	94.57	84.49
68.12	65.50	65.50	68.12	65.50	83.92	86.09	90.10	146.02	93.46	77.19	79.07	84.26	94.52	84.12
68.12	65.50	62.88	68.12	65.50	83.89	85.96	88.85	145.13	88.85	76.41	78.53	84.01	93.04	83.33
68.12	65.50	62.88	65.50	65.50	80.74	84.58	88.81	144.41	87.97	75.39	78.41	83.66	92.63	82.20
68.12	65.50	62.88	65.50	62.88	80.45	84.58	87.52	144.31	87.12	73.35	78.27	82.34	91.98	79.64
65.50	62.88	60.26	62.88	62.88	80.30	83.13	86.02	143.28	85.49	72.79	77.14	82.30	91.92	76.69
65.50	62.88	60.26	62.88	62.88	80.28	82.85	84.53	140.77	85.28	71.85	76.03	81.80	91.73	76.42
65.50	62.88	60.26	62.88	62.88	79.51	82.14	84.12	140.39	85.01	71.72	75.04	81.48	91.65	75.34
65.50	62.88	60.26	62.88	62.88	79.28	81.93	83.89	140.31	82.94	71.55	74.83	81.04	88.98	74.23
65.50	62.88	60.26	62.88	62.88	79.21	81.37	82.40	139.52	82.78	71.47	74.24	80.77	88.63	73.39
62.88	62.88	60.26	62.88	62.88	78.68	80.23	82.05	138.74	82.50	70.62	73.65	80.56	87.75	72.40
62.88	60.26	60.26	62.88	60.26	77.60	80.07	81.75	137.58	82.22	70.47	72.44	78.10	86.34	71.97
60.26	60.26	60.26	60.26	60.26	76.40	80.02	80.81	136.15	81.50	70.37	71.94	77.78	85.14	71.51
60.26	60.26	60.26	60.26	60.26	76.12	78.94	80.54	134.37	77.99	68.41	70.63	77.53	84.87	70.13
60.26	60.26	57.64	57.64	60.26	76.04	76.73	80.39	133.96	77.42	68.03	70.57	76.98	84.80	69.74
60.26	57.64	57.64	57.64	57.64	75.82	76.09	79.62	133.90	76.97	68.02	70.14	76.92	84.36	69.72

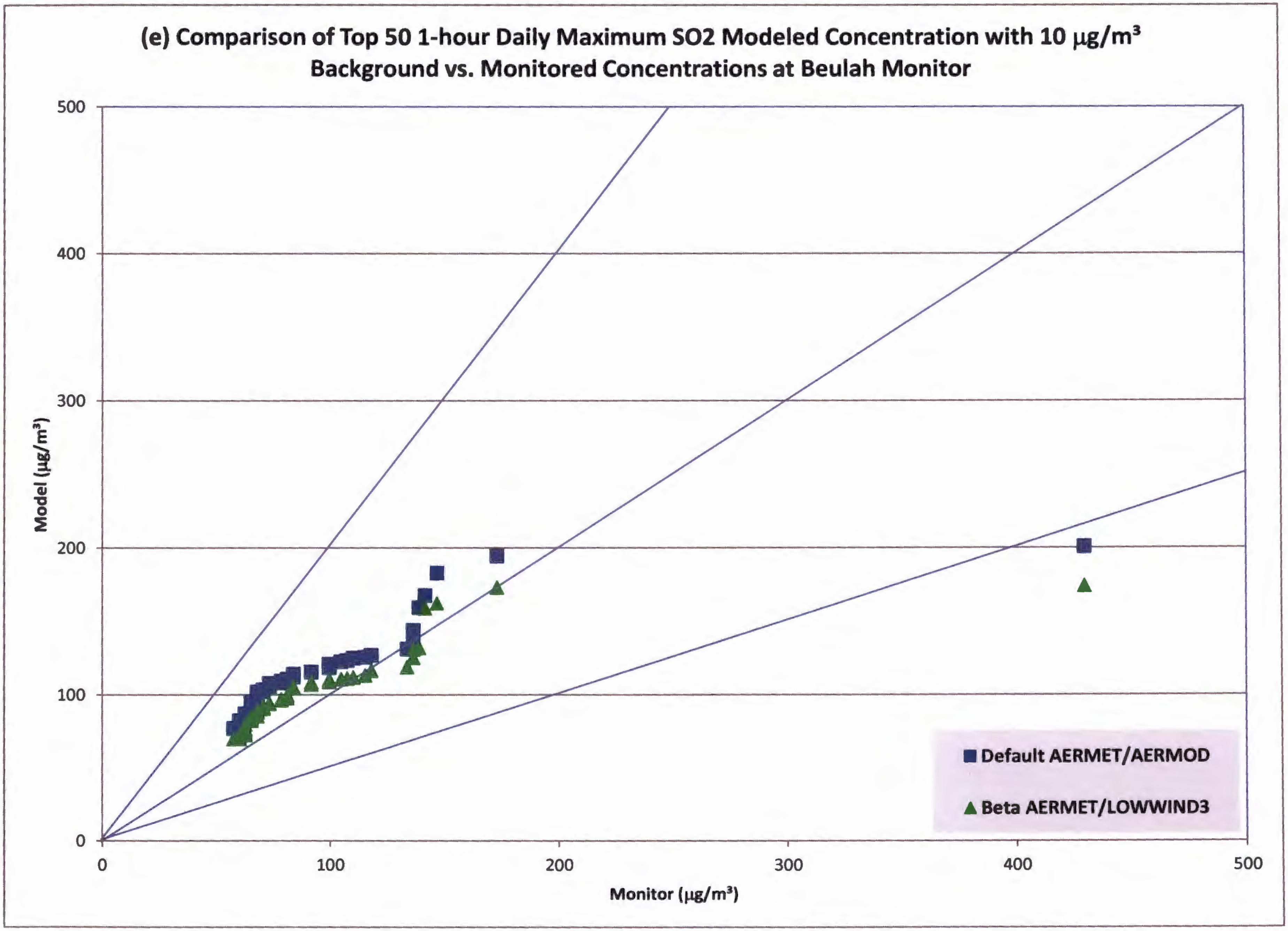


(a) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration with 10 μg/m³ Background (μg/m³) vs. Monitored Concentrations (μg/m³) at DGC #12 Monitor

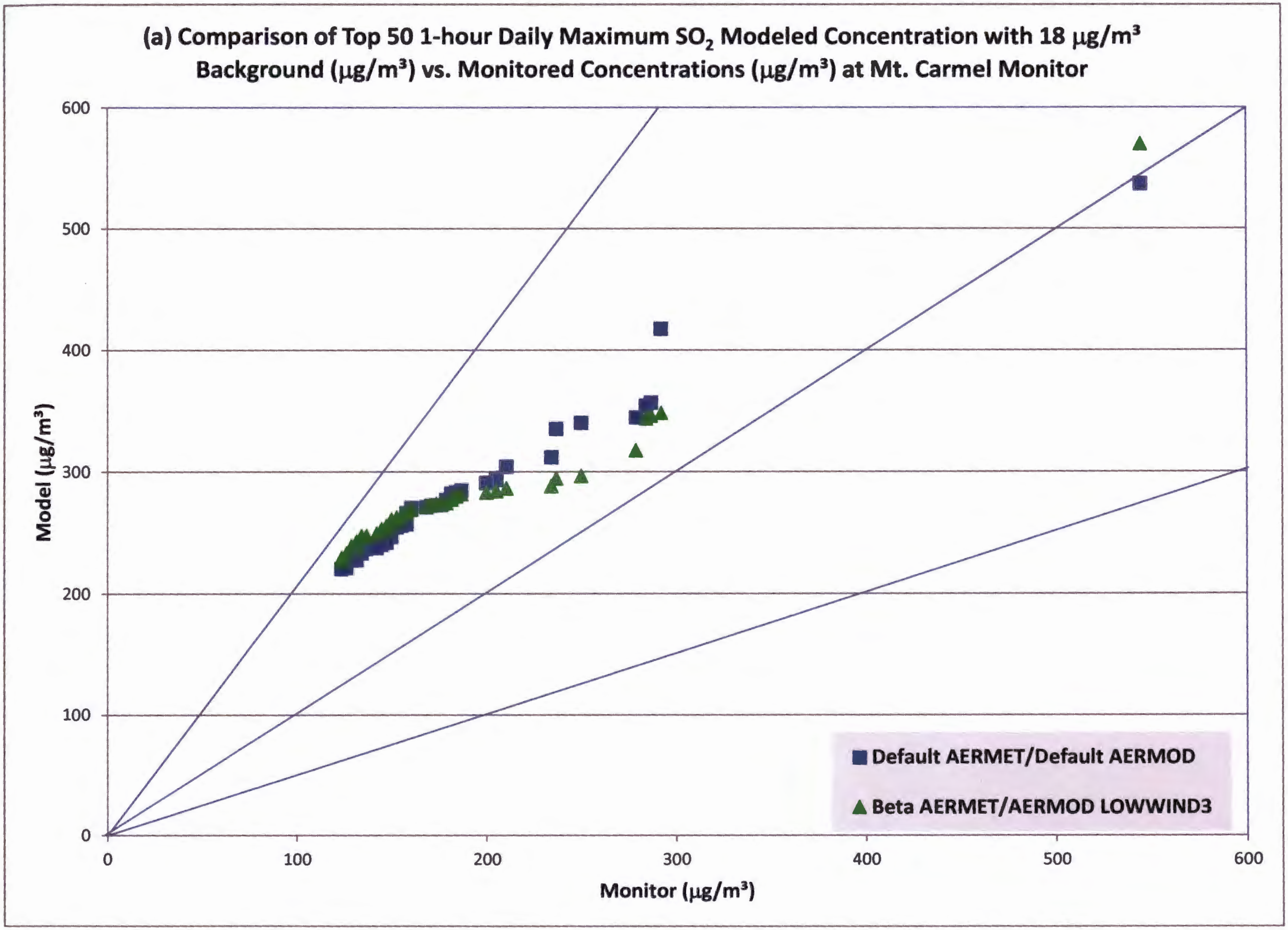

(b) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration with 10 μg/m³ Background vs. Monitored Concentrations at DGC #14 Monitor
300
200
100
0
Model (μg/m³)
0
100
200
300
Monitor (μg/m³)
■ Default AERMET/AERMOD
▲ Beta AERMET/LOWWIND3


(c) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration w/o SA with 10 µg/m³ Background vs. Monitored Concentrations at DGC #16 Monitor
400
300
200
100
0
Model (µg/m³)
0
100
200
300
400
Monitor (µg/m³)
■ Default AERMET/AERMOD
▲ Beta AERMET/LOWWIND3

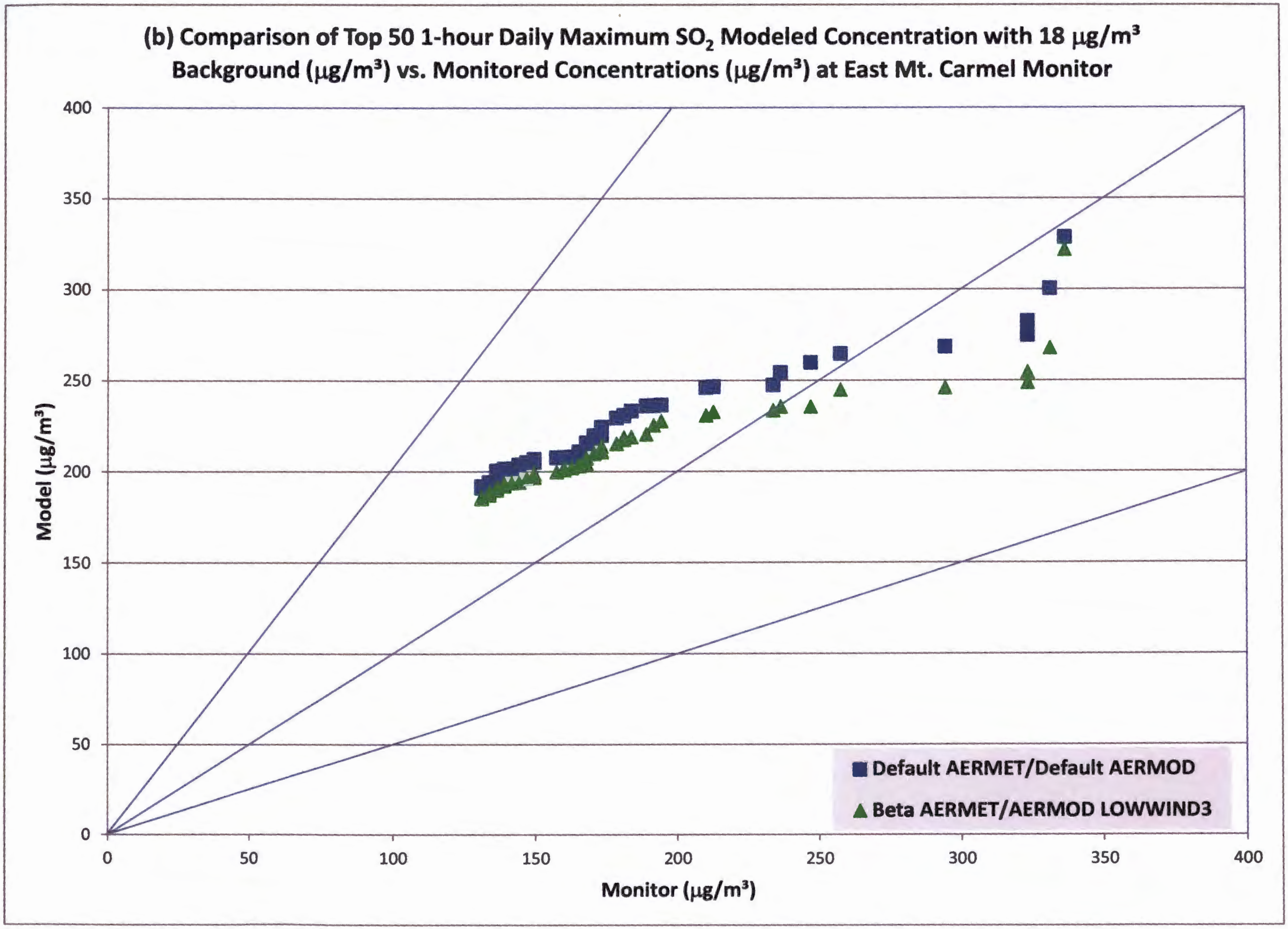

(d) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration with 10 μg/m³ Background vs. Monitored Concentrations at DGC #17 Monitor
600
500
400
300
200
100
0
Model (μg/m³)
0
100
200
300
400
500
600
Monitor (μg/m³)
Default AERMET/AERMOD
Beta AERMET/LOWWIND3

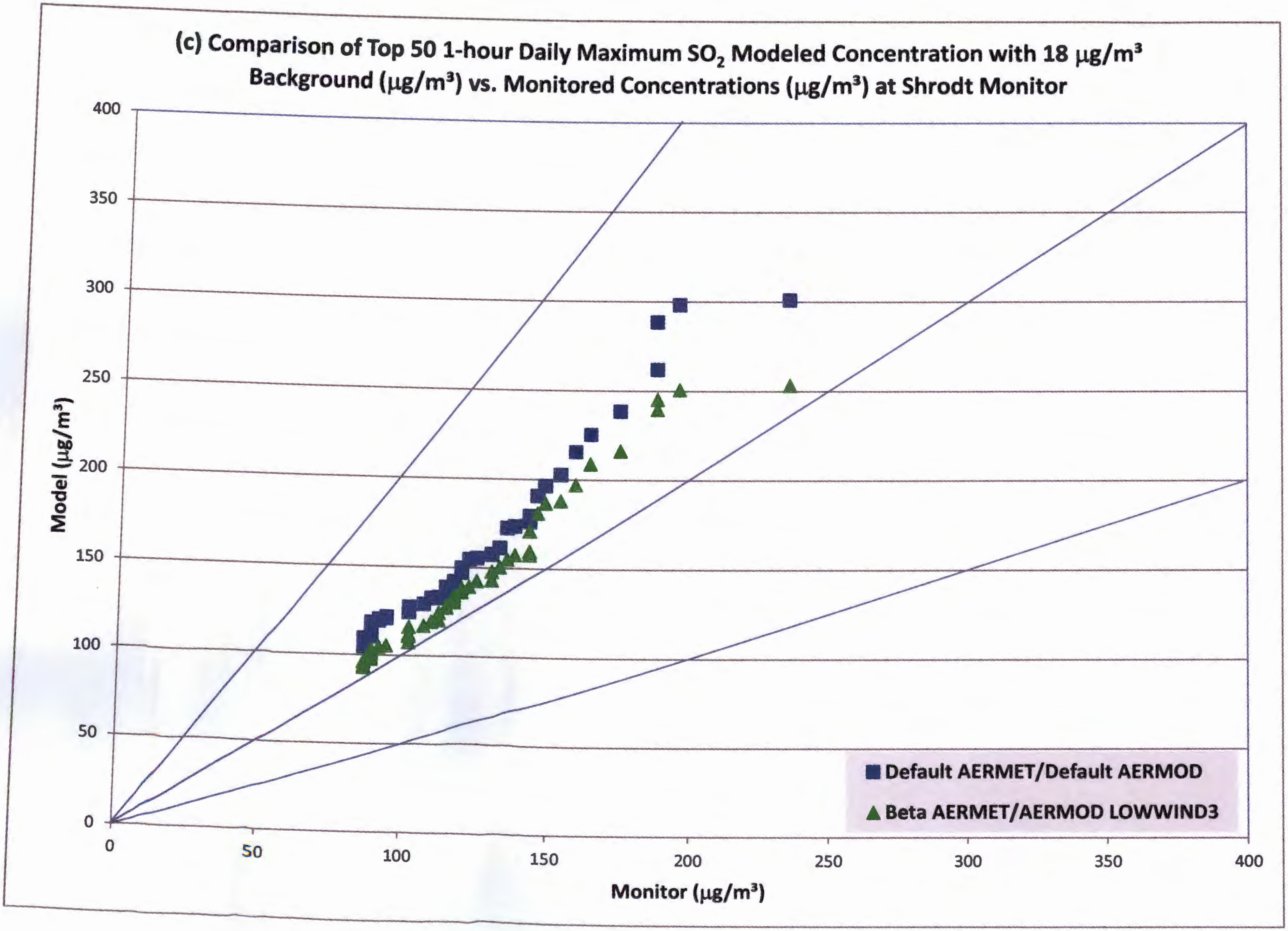


(e) Comparison of Top 50 1-hour Daily Maximum SO2 Modeled Concentration with 10 $\mu g/m^3$ Background vs. Monitored Concentrations at Beulah Monitor

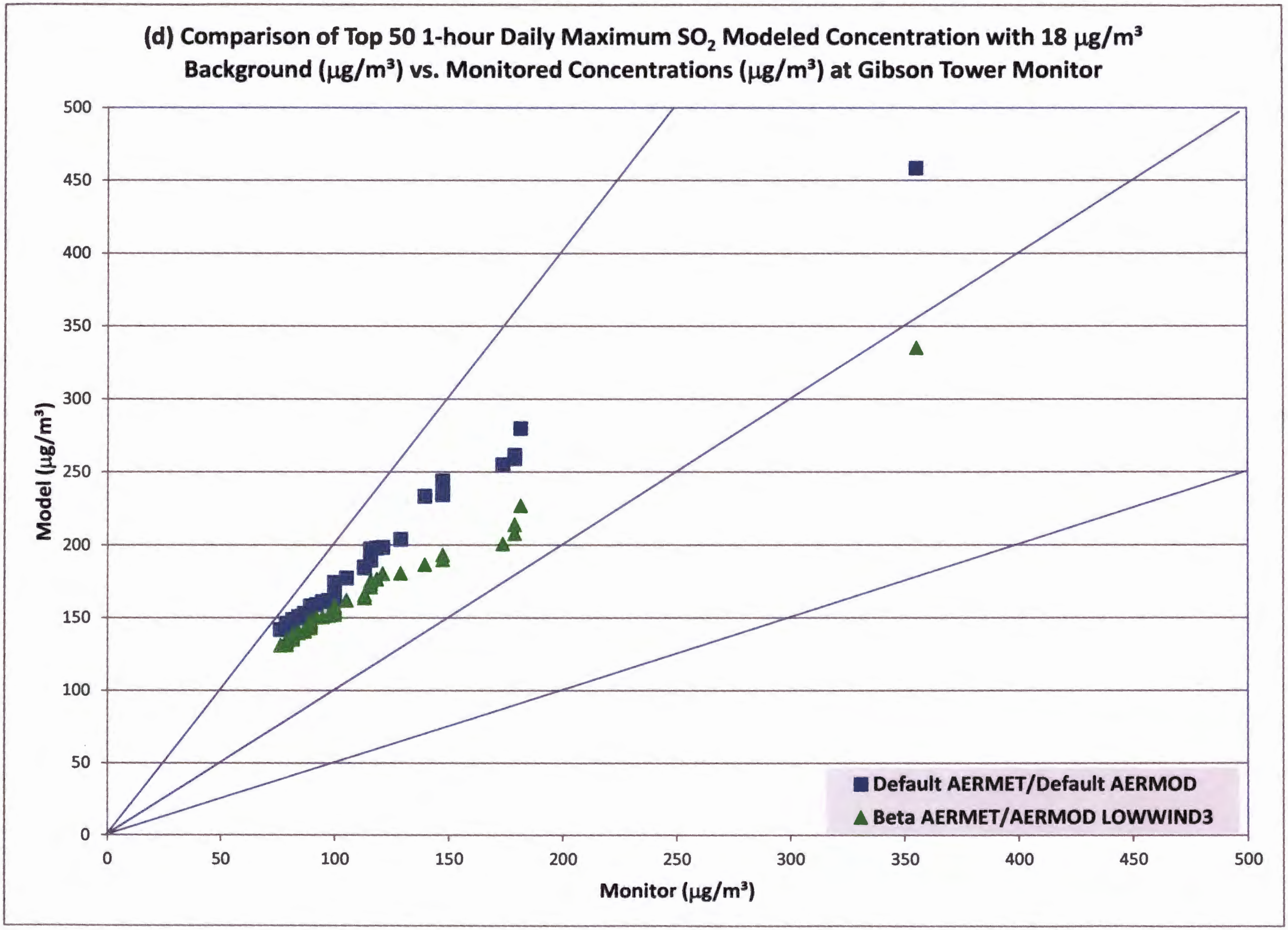


(a) Comparison of Top 50 1-hour Daily Maximum SO_2 Modeled Concentration with 18 μg/m^3 Background (μg/m^3) vs. Monitored Concentrations (μg/m^3) at Mt. Carmel Monitor


(b) Comparison of Top 50 1-hour Daily Maximum SO_2 Modeled Concentration with 18 μg/m³ Background (μg/m³) vs. Monitored Concentrations (μg/m³) at East Mt. Carmel Monitor
Model (μg/m³)
Monitor (μg/m³)
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
Default AERMET/Default AERMOD
Beta AERMET/AERMOD LOWWIND3



(c) Comparison of Top 50 1-hour Daily Maximum SO_2 Modeled Concentration with 18 µg/m³ Background (µg/m³) vs. Monitored Concentrations (µg/m³) at Shrodt Monitor



(d) Comparison of Top 50 1-hour Daily Maximum SO_2 Modeled Concentration with 18 μg/m³ Background (μg/m³) vs. Monitored Concentrations (μg/m³) at Gibson Tower Monitor